**Report of the**

# *Defense Science Board Task Force*

**on the**

# Employment of the National Ignition Facility

VOLUME II

**January 2005**

**Office of the Under Secretary of Defense**
**For Acquisition, Technology, and Logistics**
**Washington, D.C. 20301-3140**

OFFICE OF THE SECRETARY OF DEFENSE
3140 DEFENSE PENTAGON
WASHINGTON, DC 20301-3140

DEFENSE SCIENCE BOARD

25 JAN 2005

MEMORANDUM FOR ACTING UNDER SECRETARY OF DEFENSE (ACQUISITION, TECHNOLOGY & LOGISTICS)

SUBJECT: Final Report of the Defense Science Board (DSB) Task Force on the Employment of the National Ignition Facility, Volume II

I am pleased to forward Volume II of the final report of the DSB Task Force on the Employment of the National Ignition Facility (NIF). This Task Force was begun in June 2004 to examine whether the proposed NIF activation and early use plan to achieve ignition by 2010 is executable. In addition, the Task Force was to assess the extent to which stakeholders are integrated into the plan and if the plan supports the near and long term goals of stockpile stewardship.

The Task Force concludes that the NIF program is well managed and on-track. The specific recommendations are outlined in the previously published Volume I report. The attached Volume II report contains the technical background material compiled by the Task Force.

William Schneider, Jr.
DSB Chairman

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DEFENSE SCIENCE
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MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Report of the Defense Science Board (DSB) Task Force on the Employment of the National Ignition Facility

The DSB Task Force on the Employment of the National Ignition Facility (NIF) was asked to make the following assessments and provide an interim report on 31 August.

- Assess the proposed ignition and "non-ignition" high energy density experimental physics programs at the NIF. Assess the program's executability, particularly with respect to the availability of NIF and supporting technologies.
- Assess the overall balance and priority of activities within the proposed plan and the degree to which the proposed program of NIF experiments supports the near- and long-term goals of stockpile stewardship.
- Assess the extent to which the major stakeholders in NIF are effectively integrated into the plan.

The Task Force found that the National Ignition Facility and planned programs of high energy density work build on a 30-year program expanding understanding of astrophysics, weapons physics, and other scientific areas of interest. The NIF adds new regimes in pressure, temperature, and density that will, given success in achieving ignition, provide visibility into the physical phenomena at the heart of nuclear explosions, astrophysics, and other very high energy density plasmas. Hence the NIF capability to produce thermodynamic burn will provide the much-needed understanding of the most important remaining question in weapons physics, and important questions in other sciences.

Overall, the project to develop, construct and commission the NIF is well managed and on-track. Still, at the time of the report, the technical risk associated with achieving ignition in 2010 remains high. A detailed risk reduction program defined in greater detail than the current plan is needed to further reduce the risk associated with the 2010 target and beyond 2010 should that date prove too ambitious.

The Volume I report was published in October 2004. The task force compiled the supporting technical material into this second volume.

Gen Larry D. Welch, General, USAF (Ret)
Task Force Chairman

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# APPENDIX D: OVERVIEW OF STOCKPILE STEWARDSHIP AND THE INERTIAL CONFINEMENT FUSION PROGRAM

## *D.1. STOCKPILE STEWARDSHIP PROGRAM OVERVIEW*

The mission of the Stockpile Stewardship Program (SSP) is to ensure the safety and reliability of the country's nuclear weapons stockpile and the preservation of intellectual and technical competencies in nuclear weapons without nuclear testing. The program is successfully sustaining confidence in the U.S. nuclear weapons stockpile. Significant stockpile actions have been accomplished since its inception, and more are currently underway, such as the W76 Life Extension Program. In these stockpile actions, new tools developed by the SSP have been used to identify issues, analyze potential impacts, develop solutions, implement changes and in general support stockpile assessment and certification. This experience has reinforced SSP requirements for future developments in both manufacturing and scientific capabilities.

The research elements of the SSP are organized with operational aspects of a nuclear weapon, as illustrated in Figure 1. The program has been developed based on the weapon physics, material science, and engineering understanding needed for the SSP to succeed in the long term. The SSP requires a robust computational and experimental capability for success. The Advanced Simulation Computing (ASC) program within the National Nuclear Security Administration (NNSA) has developed the three-dimensional simulation capabilities required to support the SSP. Validation of these simulations is critical. Thus, facilities that provide high-fidelity tests of representative stockpile materials, components, and assemblies in realistic environments, with accurate diagnostics, are also essential to support the SSP. Where high fidelity weapon configurations and environments are impossible to achieve in the laboratory, such as is the case for many weapon physics conditions, the test and experimental program must be carefully developed to provide essential data and validation evidence from which inferences about weapon performance can be made.

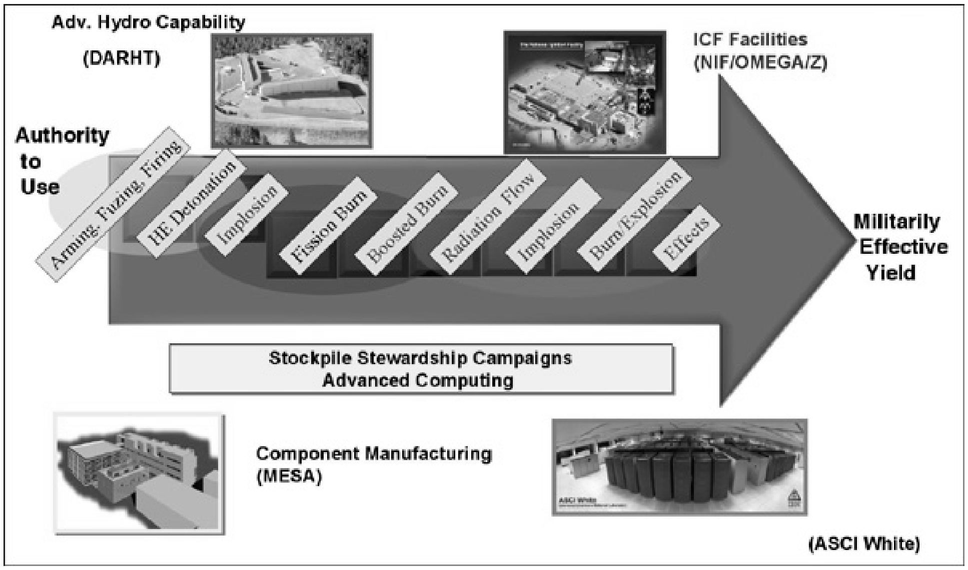


Figure 1: Stockpile Stewardship programs and facilities provide necessary research capabilities.

**Campaigns**

**Science Campaigns:**
- Primary Certification
- Dynamic Materials Properties
- Advanced Radiography
- Secondary Certification & Nuclear Systems Margin

**Engineering Campaigns:**
- Enhanced Surety
- Weapon Systems Engineering Certification
- Nuclear Survivability
- Enhanced Surveillance
- Advanced Design and Production Technologies

**Inertial Confinement Fusion and High Yield**

**Advanced Simulation & Computing**

**Pit Manufacturing and Certification**

**Readiness Campaigns:**
- Stockpile Readiness
- HE Manufacturing and Weapon Assembly/ Disassembly Readiness
- Nonnuclear Readiness
- Tritium Readiness

**Directed Stockpile Work**

**Stockpile Research and Development**
**Stockpile Maintenance**
**Stockpile Evaluation**
**Dismantlement and Disposal**
**Field Engineering, Training and Manuals**
**Production Support**

**Readiness in Technical Base & Facilities**

**Operations of Facilities**
**Program Readiness**
**Special Projects**
**Material Recycle and Recovery**
**Containers**
**Storage**
**Weapon Incident Response**

Figure 2: Elements of the Stockpile Stewardship Program.

As shown in Fig. 2, the Stockpile Stewardship Program contains three major elements. The first, Directed Stockpile Work (DSW), encompasses a broad range of activities that support the safety, security, and reliability of nuclear weapons. These activities include 1) research, development, and production associated with weapon maintenance; 2) surveillance, life extension, assessment and certification activities, baselining, and dismantlements, and 3) assessments of design, engineering, and production readiness in the nuclear weapons complex. The second major area, Campaigns, represents focused scientific and technical efforts to develop and maintain critical capabilities needed to enable continued certification of the stockpile for the long term. The third major area, Readiness in Technical Base and Facilities (RTBF), covers the physical infrastructure and operational readiness required to perform both DSW and Campaign activities. A fourth major element, Secure Transportation Asset (STA), provides the equipment, personnel, and procedures to safely move national security shipments throughout the country.

## D.2 INERTIAL CONFINEMENT FUSION (ICF) CAMPAIGN DESCRIPTION

During the operation of a thermonuclear weapon, temperatures, pressures, radiation flow, and material compositions and densities exist that do not occur elsewhere on earth. The study of phenomena in this regime is known as high-energy-density physics (HEDP). NNSA's Inertial Confinement Fusion Ignition and High Yield Campaign (ICF Campaign) provide the experimental capabilities and scientific understanding in HEDP necessary to maintain a safe, secure, and reliable nuclear weapons stockpile.

The ICF Campaign focuses on developing and using its facilities to access the HEDP regime, which begins to apply during implosion of a nuclear weapon primary. From that point onward, knowledge of HEDP is required to validate models of weapon performance, including boosted burn, radiation flow, implosion of the secondary, burn/explosion, materials properties, and weapon effects. Thus, ICF facilities address a wide range of phenomena occurring during the sequence of a nuclear explosion shown in Figure 1.

The breadth of the field of high-energy-density physics has been defined in the recent National Research Council Report, *High Energy Density Physics: The X-Games of Contemporary Science.* The phase space of HEDP as discussed in this report is shown in Figure 3.

The regions of phase space accessible to the NIF, OMEGA, and Z experimental facilities shown in the figure are approximate, and should be viewed in the context of the significant operational differences between these facilities. For example, laser facilities, because of their advantage in power, can achieve temperatures higher than those shown for small sample sizes, whereas Z-pinches, because of their advantage in energy, can reach HEDP conditions with larger experimental samples.

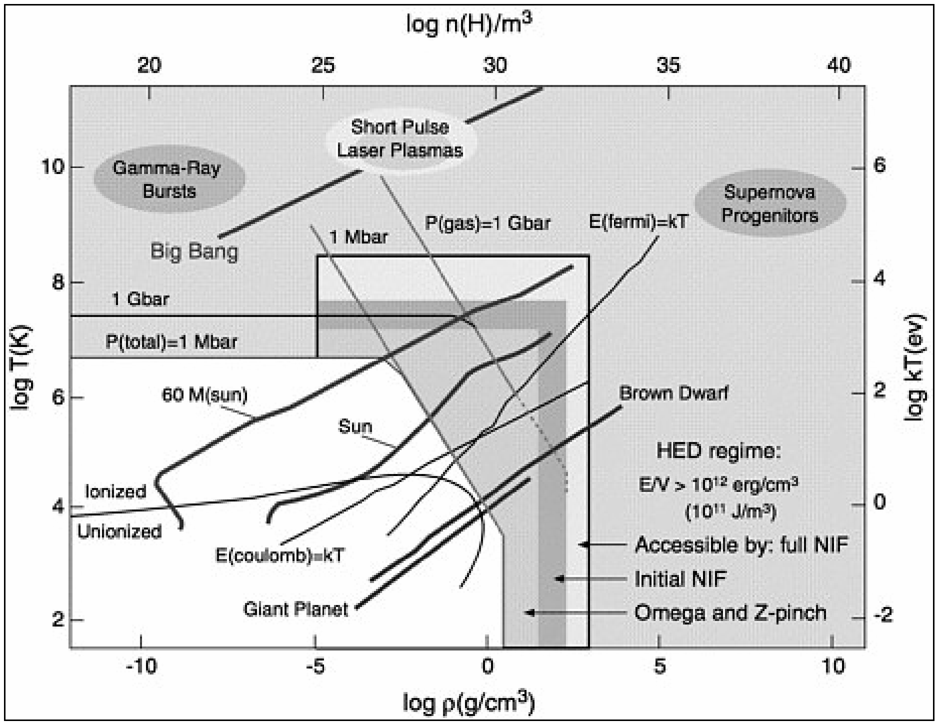


Figure 3: High Energy Density Experiments can directly explore the regimes of interesting systems (National Research Council Report, High Energy Density Physics: The X-Games of Contemporary Science).

The NNSA high-energy-density physics program encompasses activities in the following areas:

- Hydrodynamics
- Materials properties
- Radiation generation and transport
- Radiation hydrodynamics
- Laser-plasma interactions
- Physics of burning plasmas

Most NNSA activities relevant to HEDP are included in the ICF Campaign. Some related activities in target fabrication, target design, facility operations, and pulse power technology are funded via other sources within NNSA. The high-energy-density physics program within NNSA is the leading such program in the world.

## *D.3 ICF CAMPAIGN STRATEGIC GOALS AND FACILITIES*

The ICF Campaign supports the Stockpile Stewardship Program (SSP) by developing experimental capabilities and executing experiments to examine phenomena at physical conditions approaching those in a nuclear weapon. The Campaign has four strategic goals related to the study of these HEDP conditions:

1. Execute HEDP experiments necessary to provide advanced assessment capabilities for stockpile stewardship.
2. Achieve ignition in the laboratory and develop it as a scientific tool for stockpile stewardship.
3. Develop advanced technology capabilities that support the long-term needs of the SSP.
4. Maintain robust national program infrastructure and scientific talent in HEDP.

The Campaign's major technical efforts are organized to support these strategic goals. The first goal is supported by ongoing experiments at the Campaign's major laser and pulsed power implosion facilities, described further below. Development of advanced diagnostic techniques and target fabrication methods also support this effort. HEDP experiments provide material property, hydrodynamics, radiation transport, and other data needed by other SSP campaigns and the Directed Stockpile Work (DSW) program to validate advanced simulation codes used in stockpile assessments. Campaigns requiring HEDP data include three Science Campaigns (Primary Assessment technology, Dynamic Material Properties, and Secondary Assessment), one Engineering Campaign (Nuclear Survivability), the ASC Campaign, as well as the Readiness in Technical Base and Facilities program.

The second goal, achieving ignition, is supported by the indirect-drive and direct-drive ignition (IDI and DDI) programs. Ignition-related activities include experiments at the major ICF facilities in preparation for the start of ignition experiments on the National Ignition Facility (NIF); research, development, and production of ignition targets; development of advanced ignition diagnostics; and construction of cryogenic target handling systems. Procurement of beam diffractive optics, target area operations, and general user support for the NIF experimental program also contribute to the goal of ignition.

Development of advanced technology, the third goal, includes computational target design, infrastructure, and experiments related to pulsed power and other activities to assess z-pinch technology as a driver for ignition and high yield fusion. Development of high energy petawatt lasers and associated research in fast ignition also support this goal. The Campaigns Inertial Fusion Energy (IFE) activities in high-average power lasers and z-pinch technology development have been funded through specific congressional appropriations.

To accomplish the fourth goal, the Campaign provides a substantial investment in both tools and expertise. Scientific talent is attracted to the Campaign, in part, through the Stockpile Stewardship Academic Alliance and other national user programs at the ICF facilities.

Experimental infrastructure is maintained at each of the ICF laboratories, including:

- The National Ignition Facility (NIF) and Janus lasers at the Lawrence Livermore National Laboratory (LLNL)
- The Z and Saturn pulsed power accelerators at Sandia National Laboratories (SNL)
- The OMEGA laser at the University of Rochester, Laboratory for Laser Energetics (UR/LLE)
- The Trident laser at Los Alamos National Laboratory (LANL)
- The Nike laser at the Naval Research Laboratory (NRL).

Further descriptions of these facilities are provided in Appendix E. In addition to completion and initial operation of the Campaign's flagship facility, the 192-beam NIF, new capabilities are also being developed, including refurbishment of the Z facility at SNL and construction of two high-energy petawatt laser beams (OMEGA EP) at the OMEGA facility at UR/LLE. To complement ICF target development programs at each of the laboratories, General Atomics (GA) fabricates targets and target components on a production basis.

## *D.4 ICF CAMPAIGN PROGRAM ELEMENTS*

There are six major programmatic laboratories within the ICF Campaign. Figure 4 indicates those laboratories and the major activities/facilities at each. (The NNSA sponsored Academic Alliances Program is also shown.)

- **Lawrence Livermore National Laboratory**
  - **National Ignition Facility**
  - **Glass laser technology development**
  - **Indirect drive ignition**
  - **Application of HED science to stockpile issues**
  - **Diode Pumped Solid State Laser**
- **Sandia National Laboratory**
  - **Z/ZR pulsed power accelerator**
  - **Physics of z-pinches and applications**
  - **Pulsed power technology development**
  - **Application of HED science to stockpile issues (with LLNL/LANL)**
  - **Pulsed power fusion**
- **Los Alamos National Laboratory**
  - **Trident glass laser**
  - **Indirect drive ignition**
  - **Application of HED science to stockpile issues**
- **University of Rochester / Laboratory for Laser Energetics**
  - **Omega Upgrade glass laser**
  - **Omega EP Project**
  - **Direct drive physics assessment**
  - **Application of HED science to stockpile issues (with LLNL/LANL)**
  - **Technology development for the ICF program**
- **Naval Research Laboratory**
  - **Nike KrF laser**
  - **Application of HED science to stockpile issues (with LLNL/LANL)**
  - **Direct drive target design**
  - **KrF laser technology development**
- **General Atomics**
  - **Target fabrication**
  - **Cryogenic target technology**
- **Academic Alliances Program**
  - **National Laser User Facility (NLUF) Program (LLE)**

**1**

Figure 4: ICF Campaign programmatic elements and major activities/facilities.

The ICF Campaign is unique amongst NNSA programs in that major programmatic activities are executed outside of the weapon laboratories. As can be seen from Figure 4, LLNL and LANL are primarily responsible for indirect drive ignition and HEDP in support of the stockpile. LLNL and LANL execute collaborative activities in these areas with SNL, LLE, NRL, and GA. The physics of direct drive fusion is pursued primarily at LLE and NRL, with collaborative activities at the other sites. The Academic Alliances Program supports 23 university grants in HEDP across the nation. Experimental time at OMEGA and associated funding is allocated to university and other users external to NNSA via the National Laser User Facility (NLUF) Program.

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# APPENDIX E: SUMMARY OF NIF ACTIVATION AND EARLY USE PROGRAM

## *E.1 INTRODUCTION AND OVERVIEW*

This appendix summarizes the NIF Activation and Early Use Program (AEUP) as presented to the task force in the summer of 2004.

The NIF AEUP defines the activities proposed to be undertaken on NIF between CY 2004 and CY 2010, including the NIF Project itself. Details are still being addressed and a formal NIF Activation and Early Use Plan document will be assembled for NNSA approval. The NIF AEUP includes the following elements:

NIF Project Completion: The Program includes the plan to complete NIF and the schedule by which NIF beamlines will be installed, commissioned, and activated. Key parameters include the amount of facility time available for laser commissioning and activation, and user experiments and various facility specifications such as the available energy vs. time.

Detailed Campaign Plans: The second major element of the Program is NNSA campaign goals and plans for early use of the NIF. In addition to the ICF Campaign, those using the NIF are the Science Campaigns, which include Primary Assessment Technology, Secondary Assessment Technology, Materials Dynamics, Nuclear Survivability, and Nuclear Weapons Effects. Experiments supporting Directed Stockpile Work will also be performed.

Experimental Support Technology: The third principal component of the Program is the specialized hardware, equipment, and other activities that are not part of the NIF construction project, but are needed to make it a fully functional facility. These include: (i) construction and installation of nearly all experiment diagnostics; (ii) fielding of the fixtures and system to hold cryogenic-conditioned targets; (iii) special replaceable optics to produce desired focal spot shapes and required by users to execute experiments; and (iv) operation of the NIF target area and associated equipment.

Special Issues: There are also special issues requiring consideration when framing the plan, such as classification, use of special materials (e.g., beryllium, uranium, tritium) and containment.

The proposed NIF AEUP reviewed by the Defense Science Board also includes the Advanced Radiographic Capability (ARC). ARC involves the addition of equipment at NIF to allow an existing beamline to provide a short duration (1-10 picosecond), high-energy laser pulse. ARC is primarily intended to provide a high-energy x-ray backlighting diagnostic capability for NIF. There is not a consensus in the ICF community regarding implementing ARC before 2009; the concern is it may disrupt the NIF baseline.

The NIF AEUP must be consistent with the needs of the user communities, primarily in ignition and weapons physics. The challenge is to formulate a plan that is consistent with the budget and all planned activities in the four areas above.

In the early stages of NIF use planning, it was determined that user requests exceed the number of laser shots available, NIF diagnostic and supporting hardware, program capability, and associated budget by approximately a factor of two. Lower priority activities were removed to ensure the plan was consistent with the budget and other constraints. The current NIF AEUP synchronizes the campaign requirements, the project schedule, and the NIF supporting technologies and capabilities, and makes them self-consistent with the budget. It provides for the first NIF ignition experiments in 2010. This program also contains annual milestones for weapons science data to support ongoing stockpile assessment and certification.

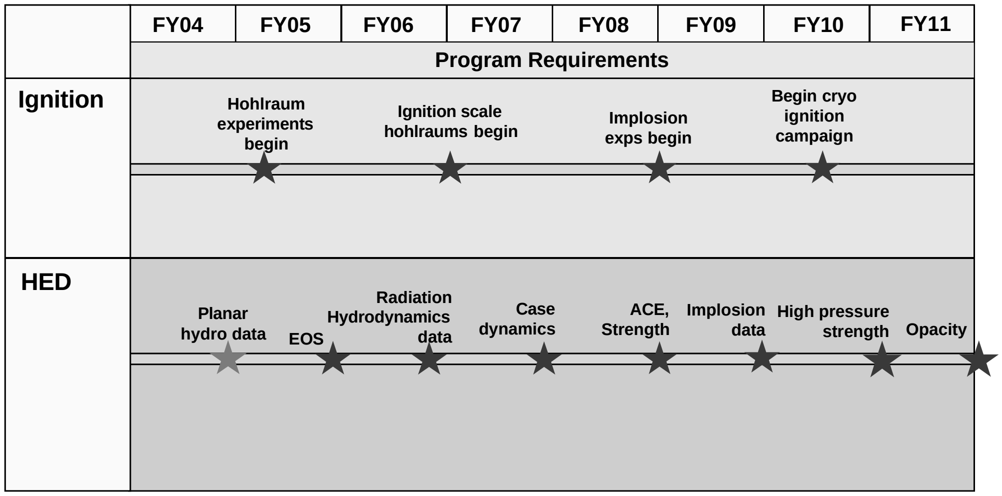



Figure 5: NIF Activation and Early Use Program goals include start of cryogenic ignition campaign in FY 10 and yearly high energy density physics data.

Figure 5 depicts the major milestones for the proposed NIF Activation and Early Use Program. The Ignition Campaign culminates in first ignition experiments in CY 2010. A major weapon science milestone in areas such as materials properties, radiation transport, and hydrodynamics is proposed each year. The weapon science plan includes studies of radiation transport on the first cluster (i.e., 48 beams), early measurements to prepare for strength measurements in special materials, and hydrodynamic experiments. In the current program, approximately 80% of the total shots are allocated to weapons science, including the ignition campaign. Approximately 15% of the shots will be allocated to users external to NNSA such as the university community and the Department of Defense Nuclear Weapons Effects Test user community. The remaining 5% is set aside as contingency.

There are important international connections, though these were not discussed extensively with the task force. The Commissariat à L'Énergie Atomique (CEA) in France is building a 240-beam laser known as Laser Megajoule (LMJ). LMJ uses many of the same technologies employed in NIF; much of this technology was jointly developed between the United States and CEA. Continued cooperation with both the French and the British is anticipated in programmatic areas.

## *E.2 NIF PROJECT COMPLETION AND ACTIVATION*

The National Ignition Facility is well on its way to completion. The milestone chart (Figure 1) shows the status of the major milestones. Overall NIF project completion currently stands at ~80%. The conventional facility is 100% complete, as is the beam path infrastructure.

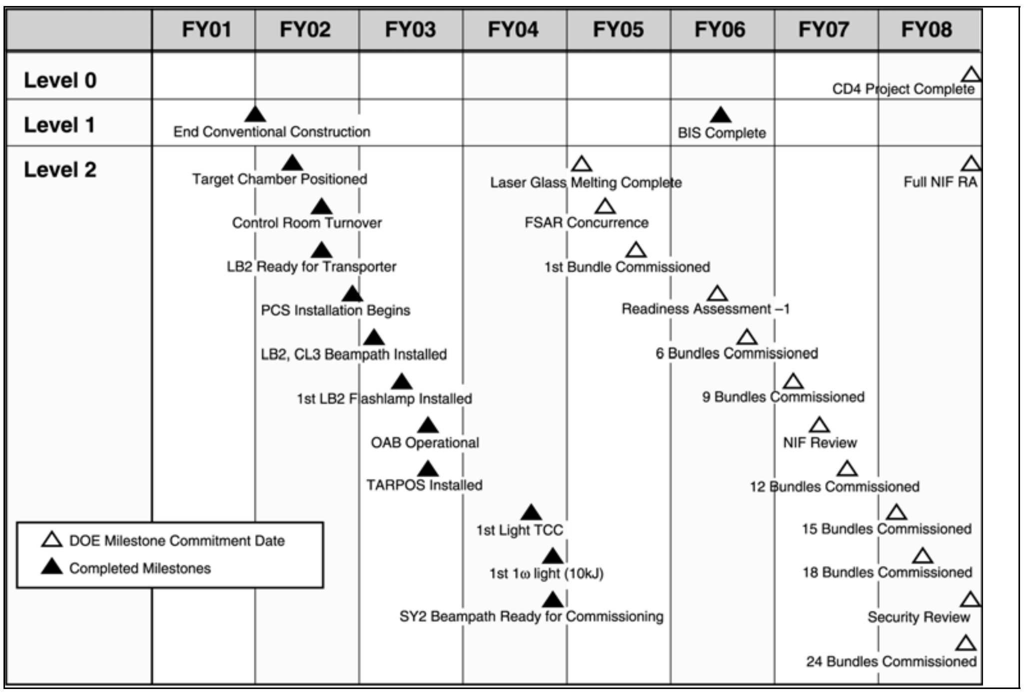



Figure 6: NIF Project milestone schedule

Many of the large optics for NIF are in place. All of the laser glass for NIF has been procured and approximately 50% has been finished. The large optics for NIF are ~65% complete, and 90% of the contracts have been placed. NIF is thus now well into the procurement phase for the optics for remaining beamlines. The first four beams of NIF have been installed and activated, and are used for experiments. The remaining effort on the project (FY 2004 – FY 2008) will be focused on assembly, installation, and commissioning of the remaining beamlines, with all 192 beamlines installed and commissioned by the end of FY 2008. The NIF Project's Earned Value Management System indicates cost and schedule performance indices are near nominal values of 1.0 and 0.99, respectively.

As can be inferred from Figure 6, the planned installation rate of equipment in the NIF building increases over the course of the project in order to meet bundle deployment and commissioning milestones. The NIF Project has been planning carefully for this increase in the rate of installing components, with current planning ramping up component production to a peak beginning in mid-FY07. The completion of first cluster in June 2006 will demonstrate the NIF Project's ability to assemble and commission beamlines at the rates required for Project completion.

The installation and activation of the first four NIF beamlines was called "NIF Early Light" (NEL). NEL was completed in mid-FY2003 and consisted of assembly, installation, commissioning, and transport of these beamlines to the target chamber center. The purpose of NEL was to demonstrate end-to-end functionality of all major subsystems required for full facility operation. The NEL strategy has been successful and has resulted in over 300 full system shots for laser performance and physics experimental campaigns. Approximately 100 shots have been used for experimental activities, including target positioning, beam pointing, and diagnostics commissioning. These experiments have successfully produced physics data for SSP researchers, while the remaining 200 shots have been conducted for laser commissioning and laser performance tests. These first four beams of NIF have already demonstrated the performance (on a per-beam basis) required for the full laser system.

The first diagnostics installed on NIF for NEL have been used to verify and validate laser beam performance to target chamber center, while also providing high-quality physics data for experimenters, including data for the SSP. Diagnostics installed and activated during NEL include the Static X-ray Imager (SXI), the Flexible X-ray Imager (FXI), Streaked X-ray Detector (SXD), the Full Aperture Backscatter System (FABS), the Near Backscatter Imager (NBI), and the Velocity Interferometer System for Any Reflector. The first SSP experiments have fielded gas-filled targets to study the physics of laser-plasma interactions (LPI). Results from this experimental campaign, shown in Figure 7, were used to compare with computer models of laser-plasma interaction to validate that energetic NIF laser beams can propagate through plasmas to deliver energy to ICF targets.

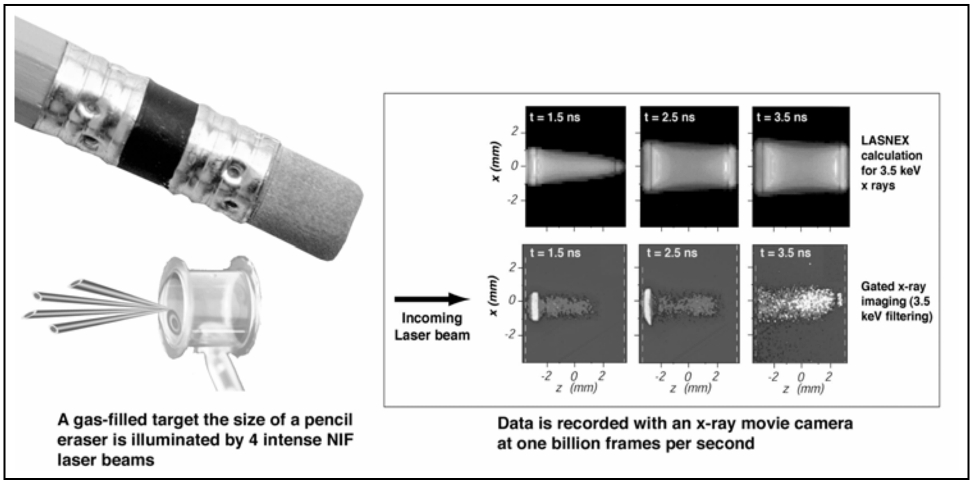



Figure 7: Four NIF beams incident on a 7-mm long gas-filled target the size of a pencil eraser are shown on the left. These beams produce intense x-rays that are measured and compared with computer calculations on the right.

Other experiments have been performed to study complex hydrodynamic phenomena, which have broad applicability to stockpile stewardship as well as to the study of astrophysical phenomena such as supernova mechanisms. These experiments have also provided valuable information for code validation, and to refine the materials models used in those codes. The hydrodynamics experimental campaign, which also was the first joint LLNL/LANL campaign conducted on NIF, served as the basis for completion of a major Department of Energy (DOE) milestone in FY 2004. Figure 8 shows one of the experimental radiographs of a double jet experiment in which supersonic jets of aluminum of different size are driven into low-density carbon foam. The complex interaction of these two jets can be seen in the figure, which was radiographed using a separate beam of NIF delayed in time by 15 nanoseconds that was directed to an off-center x-ray backlighter foil. This experiment demonstrates the flexibility of NIF to provide beams for both interacting with targets and providing diagnostic x-ray sources for radiography.

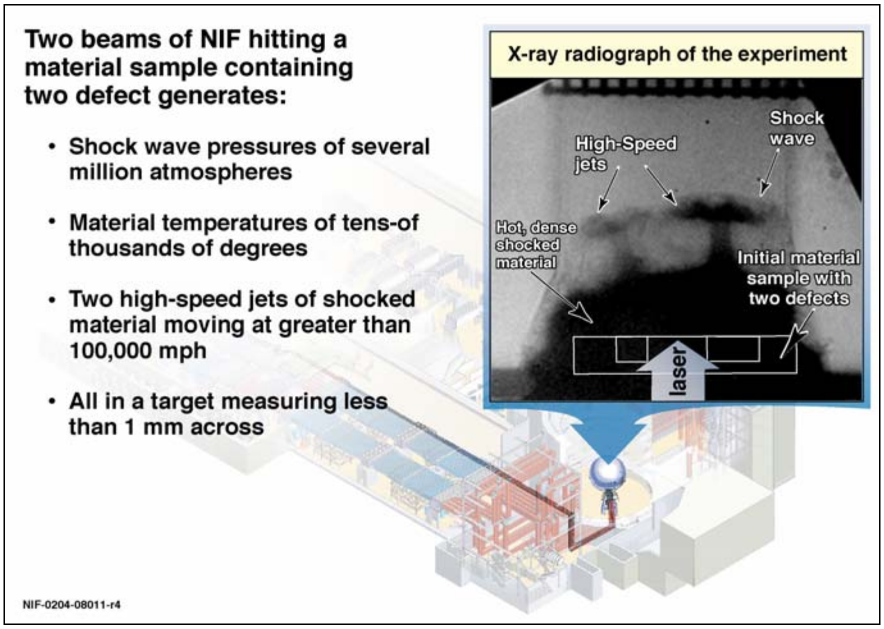



Figure 8: The first joint LLNL/LANL hydrodynamic campaign provided this x-ray radiograph of a double jet experiment.

Summarizing, essentially all full NIF performance capabilities have been demonstrated using single beams of NIF or the full quad available. These include delivering record-setting single beam energies equivalent to a full NIF energy of 5.0, 2.2, and 2.0 megajoules at 1ω, 2ω, and 3ω; delivering a record-setting energy of 106 kJ of infrared light in four beams; producing high-quality beams with better than 6% beam contrast at 1ω, 1% beam energy balance, and beam-to-beam time of better than 6 trillionths of a second.

NIF laser beam installation, commissioning and activation is planned by the NIF Project in close coordination with the user community to make beams available in a manner consistent with the NIF AEUP, and in support of the goal of Ignition 2010. Figure 9 shows the planned deployment of additional NIF laser beams.

In FY 2005, the first bundle of eight beams will be deployed. Clusters of 48 beams will then be installed and commissioned, with the full 192-beam NIF completed in 2008. From the user perspective, the first cluster of 48 beams will be available beginning in late 2006. The additional clusters will be installed by project completion at the end of FY 2008, but will not be available for user experiments until the middle of FY 2009. This plan for cluster availability is dictated by both the needs of the NIF Project and the fact that the user community has limited capacity in this time frame to characterize new hohlraum configurations, develop and commission new diagnostics, and provide user-supplied optics for special experimental needs.

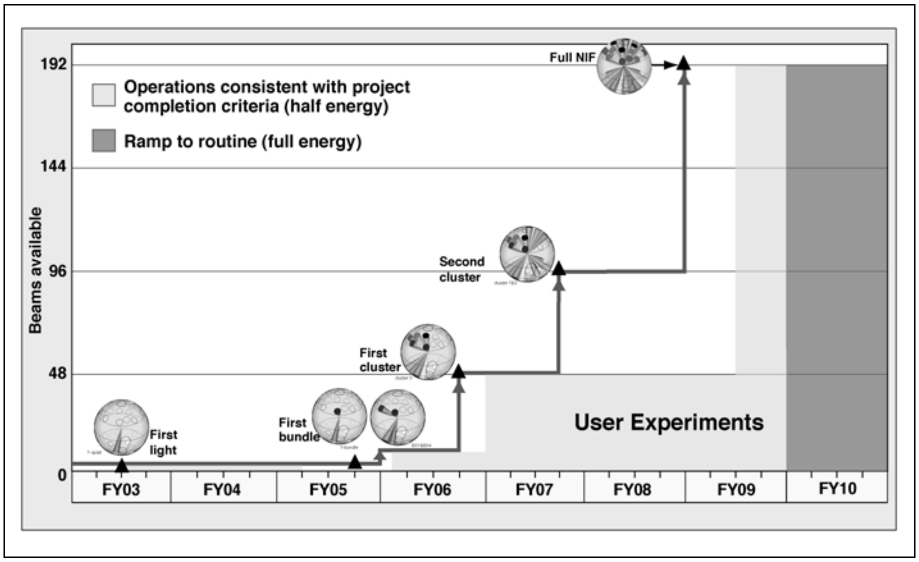



Figure 9: Planned deployment of additional NIF laser beams.

NIF will be available routinely with all 192 beams available for users beginning in the third quarter of 2009. Full energy will be demonstrated on one bundle (8 beams) by the time of Project completion in 2008. The entire facility will be ramped up to routine full energy operation in the 2010 timeframe.

As described earlier, this appendix describes the NIF AEUP as presented to the task force. The NIF Activation and Early Use Plan continues to evolve as the NNSA's understanding of how to best support the goal of Ignition 2010 and the overall Stockpile Stewardship Program develops. NNSA is examing mechanisms to assure NIF milestones measuring facility activation will be aligned with the planned budget and approved AEUP.

## E.3 IGNITION PROGRAM

Two fusion ignition architectures for laser implosion have been proposed, as shown in Figure 10. In the indirect drive ignition (IDI) scheme, laser radiation is directed into a hohlraum. The laser light interacts with the high-Z hohlraum walls and is converted to x-rays. This source of x-rays produces a very uniform illumination that compresses and implodes the capsule and produces ignition conditions. With the direct drive ignition (DDI) scheme, the laser beams strike and compress the capsule directly.

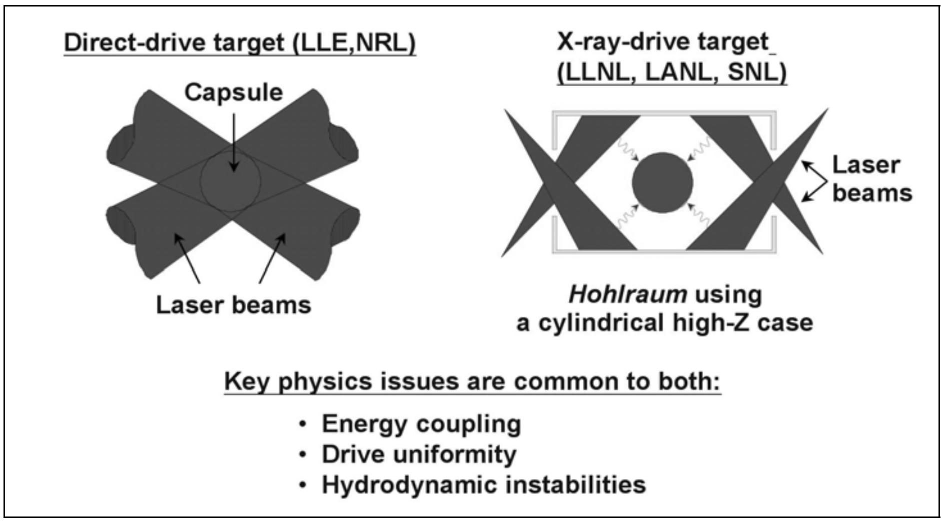



Figure 10: X-ray-drive and direct-drive ignition schemes.

Direct drive is an alternative that potentially offers a back-up for ignition and in the longer term possibly higher gain. The physics basis for indirect drive was formulated in the 1980s and 1990s, and was reviewed by the National Academy of Sciences and other groups[1]. The physics requirements for indirect drive were fundamental to setting the specifications for NIF; NIF is being constructed in a manner "not to preclude" direct drive.

1. Review of the Department of Energy's Inertial Confinement Fusion Program" (Commission on Physical Sciences, Mathematics, and Applications, National Research Council), National Academy Press, Washington, DC, 1997

*Indirect Drive Ignition*

The ignition program for indirect drive is focused on four components, as depicted in Figure 11. Each area and associated activities is described briefly below.

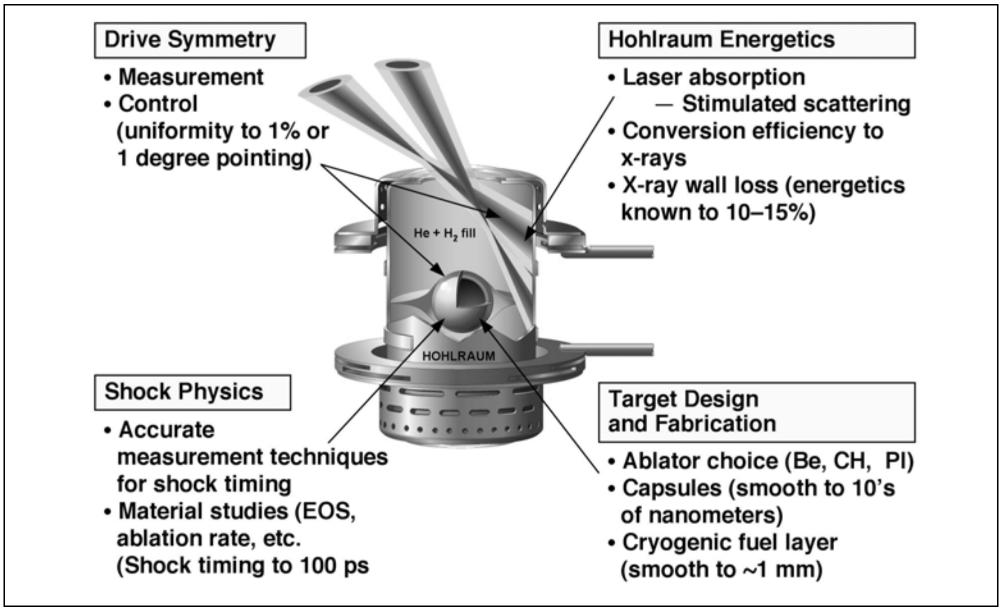



Figure 11: The National Ignition Program has four components.

1. Hohlraum Energetics: The goal of the hohlraum energetics component is to deliver a pulse of x-ray energy to the capsule that meets all requirements. As laser light interacts with the high-Z hohlraum wall and produces x-rays, plasma instabilities are generated that can diffract, absorb, and scatter the incoming beams. Activities in this area are focused on minimizing the effects of plasma instabilities, optimizing the efficiency of the hohlraum, and providing the required temporal profile of x-ray radiation at the capsule. The hohlraum energetics element is also responsible for specifying the diffractive optics to be used in the ignition campaign.

2. Drive Symmetry: Drive symmetry involves achieving approximately 1% symmetry in x-ray drive illumination at the capsule surface. NIF will use "inner" and "outer" cones of beams at each end of the hohlraum, as shown in Figure 12, to satisfy this time-dependent symmetry constraint. To achieve the required symmetry,

the position of the laser beams on the hohlraum wall and the time history of the laser pulse (i.e., the "laser pulse shape") must be precisely controlled throughout the duration of the capsule implosion. Activities in this area focus on developing techniques to diagnose and control symmetry at all points during the implosion.

3. Implosion Dynamics: Ignition targets use a highly shaped laser pulse (Figure 12). The pulse shape is shown in Figure 12 below. As the implosion proceeds, a number of distinct shock waves are produced within the capsule. The shock waves must be timed to pass through the DT fuel layer sequentially, for efficient fuel compression, and coalesce after they exit the fuel layer. A hot spot is formed at the center of the compressed capsule, causing fusion burn to propagate outwards through the dense fuel. The goal in implosion dynamics is to provide the capsule design and laser pulse shape with the required hydrodynamic stability and shock coalescence. The implosion dynamics program develops the diagnostic techniques and understanding required to experimentally time shocks to the required accuracy, and also validates the performance of advanced ablators and fill tubes. The latter will be an important focus of this program in the next several years.

4. Ignition Implosions and Fabrication: Activities in this area are focused on developing fully characterized ignition targets that meet specifications, as well as the means to produce these targets in sufficient quantity to support the ignition campaign. Ignition targets use a mix of solid and gaseous deuterium-tritium fuel held near the triple point (~18 K) at cryogenic conditions. An important element of this program is the development of the cryogenic systems to fill ignition targets with deuterium-tritium and maintain them at the required conditions.

A schematic of the NIF indirect-drive ignition target is shown in Figure 12. The baseline target reviewed in the mid- 1990's uses a plastic ablator. It is designed to be filled at high pressure and room temperature (~20,000 psi) via a diffusion process, and transported to the target chamber under cryogenic conditions.

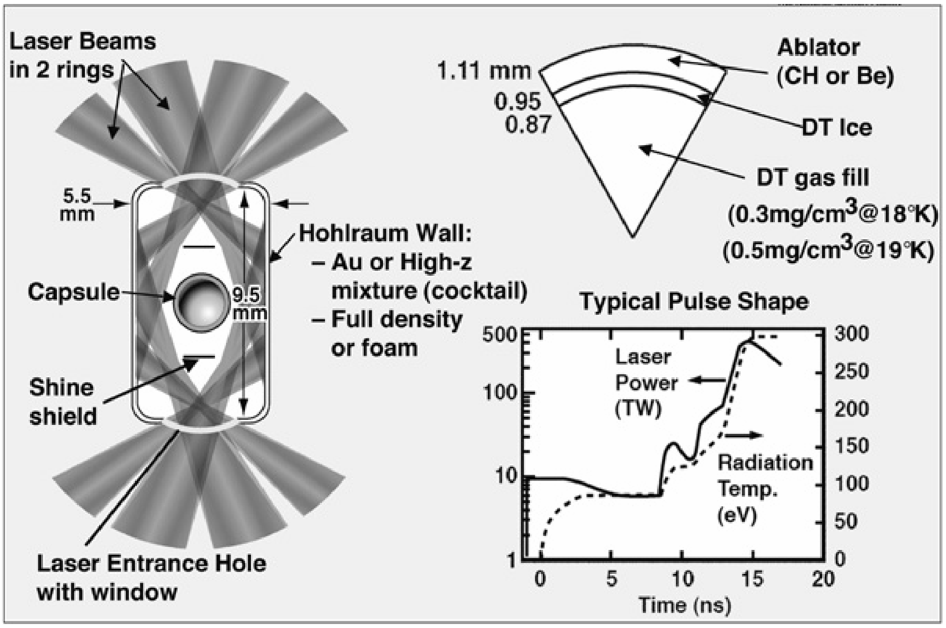



Figure 12: Schematic of NIF indirect-drive ignition target.

It has been known for some time that capsules with beryllium ablators offer improved target performance; however, these targets have been historically difficult to fabricate and characterize. Recent progress in fabrication and characterization as well as the realization that these targets may be filled with a potentially simpler fill-tube cryogenic system have led to a beryllium-ablator capsule with fill-tube being adopted as the point design for the Ignition 2010 program. The beryllium ablator is doped with copper to improve target performance. Figure 13 shows a schematic of a hohlraum with a beryllium ablator/fill-tube capsule and the associated fill-tube cryogenic system.

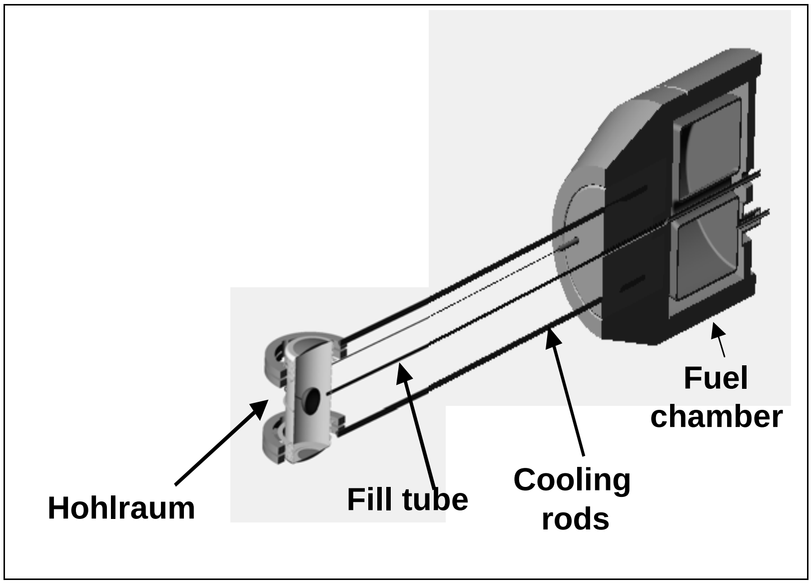



Figure 13: Schematic drawing of doped-ablator beryllium target with fill-tube cryogenic system.

Ignition planning has been an active component of the national ICF Program since 1997. The ignition plan has been revised to accommodate beryllium targets and a fill-tube cryogenic system and incorporated into the NIF Activation and Early Use Program. While the indirect drive ignition program will focus on capsules with beryllium ablators, plastic ablators and other options will be maintained and developed as part of the overall risk reduction program. Figure 14 shows the schedule for indirect drive ignition.

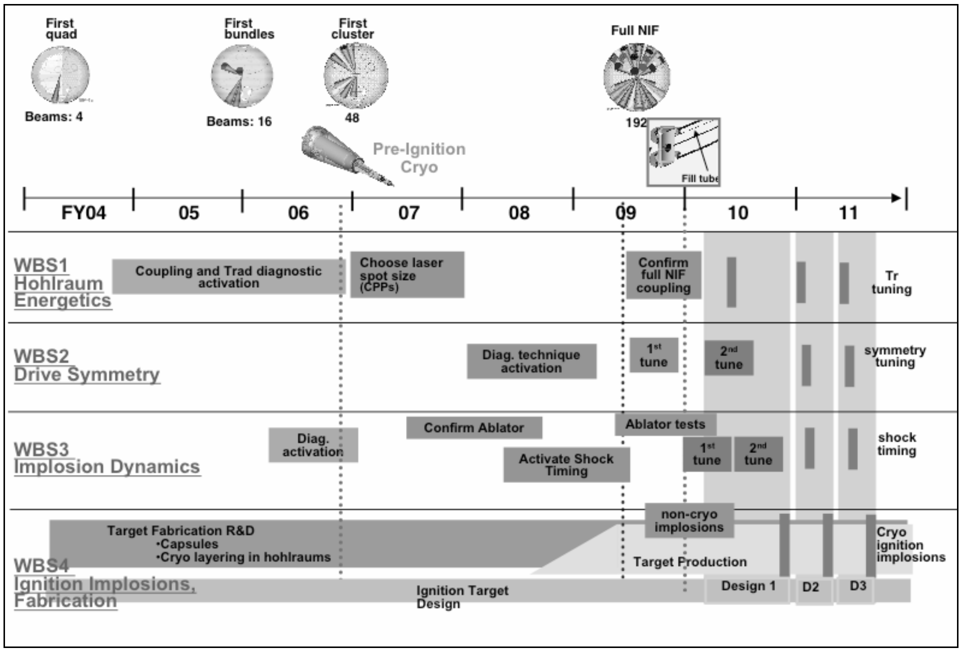



Figure 14: Schedule for indirect drive ignition.

The indirect drive ignition demonstration will commence in mid-2010 with a series of experiments to tune the laser pulse shape, drive symmetry, and shocks delivered to the target. The schedule for indirect drive ignition features an experiment using "Design 1" (D1), which will be executed in the third quarter of CY2010. A second target, known as D2, is scheduled for the fourth quarter of CY2010. Target D1 will be done at an energy of ~ 1MJ and is intended to be a pre-ignition target to test the integration of all the program elements necessary to achieve ignition. A third target design will be investigated after D2 and is primarily intended to be a slightly "retuned" version of target D2.

The parameter space over which designs D1, D2 and D3 are expected to ignite is shown in Figure 15. The D3 target design would be a different point in the phase space as shown in Figure 15 for the D2 target design. Figure 15 shows the calculated phase space for indirect drive ignition has increased in the past 8-10 years. This is due to improved optimization of target performance as well as the use of advancements such as the copper-doped beryllium ablators and high-Z mixtures of materials ("cocktails") in hohlraums. Much of the activity in the indirect drive ignition program in the next five years will be devoted to experimental validation of these calculated improvements to target performance.

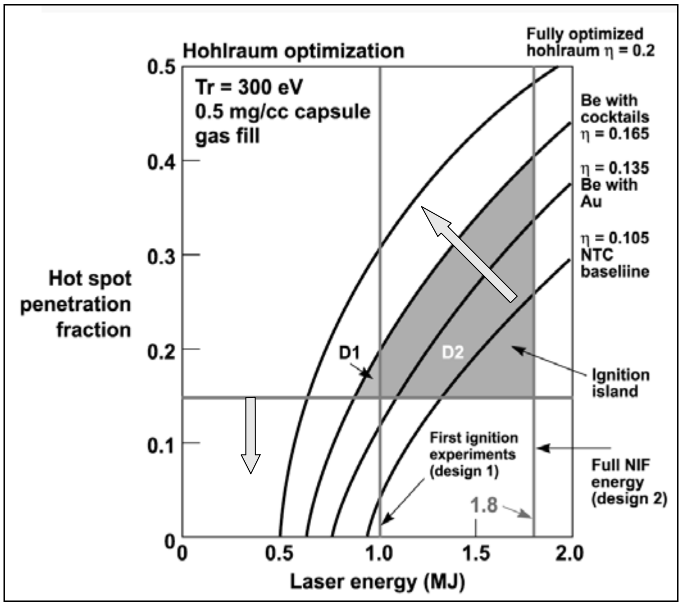



Figure 15: The phase space over which indirect drive ignition is expected.

The national ICF Program has examined the risks for the indirect drive ignition program and proposed a series of measures to mitigate these risks. A national risk mitigation program was presented to the task force and will be documented in the forthcoming NIF Activation and Early Use Plan document. A summary of the risks and the effect implementation of the mitigation program is expected to have in lowering them are presented in Figures 16-17. As shown in the "mitigation" column, it is expected that many of the risks cited in the figures can be reduced to the low to moderate level prior to the year 2010.

The National Ignition Facility

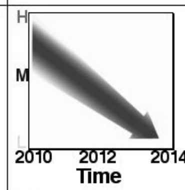
| Category | Risk | Mitigation |
|---|---|---|
| Schedule | Ignition requires integration of many complex tasks |   |
| | Limited High Fluence Shots | M → L |
| Targets | Target Options too restricted | L |
| | Is the national Target Fab. program robust enough? | H → L |
| Cryogenics | Be targets allow DT, but not D2 | H → L |
| | Ignition experiments require a reliable, stable Cryo system | H → L |

Figure 16: Summary of Schedule, Target, and Cryogenic Risks

The National Ignition Facility

| Category | Risk | Mitigation |
|---|---|---|
| Physics | Energetics inadequate for Design 1 ignition | H → M |
| | Symmetry and Energetics affected by LPI | M |
| | Fill-Tube Perturbation | M → L |
| | Sputtered Be ablator performance (including non-uniformity and roughness) | L |
| | Graded-doped designs untested by experiments | L |

Figure 17: Summary of Physics Risks

The indirect drive ignition program is an integrated activity that uses all of the major facilities in the ICF Program, namely NIF, OMEGA, and Z/ZR. A summary of the experiments planned for each of these facilities is shown in Figure 18. The experiments shown above fall into the following categories:

- Experiments used to validate calculations of advanced ablator performance, fill tubes, and other aspects of target behavior

- Experiments to validate diagnostic techniques required for measurements of capsule symmetry, shock timing, and hohlraum radiation drive

- Experiments to determine the phase plate set to be used in NIF ignition experiments

- NIF ignition campaign, including experiments to tune symmetry, radiation drive, and shock timing, culminating in cryogenic ignition demonstration experiments

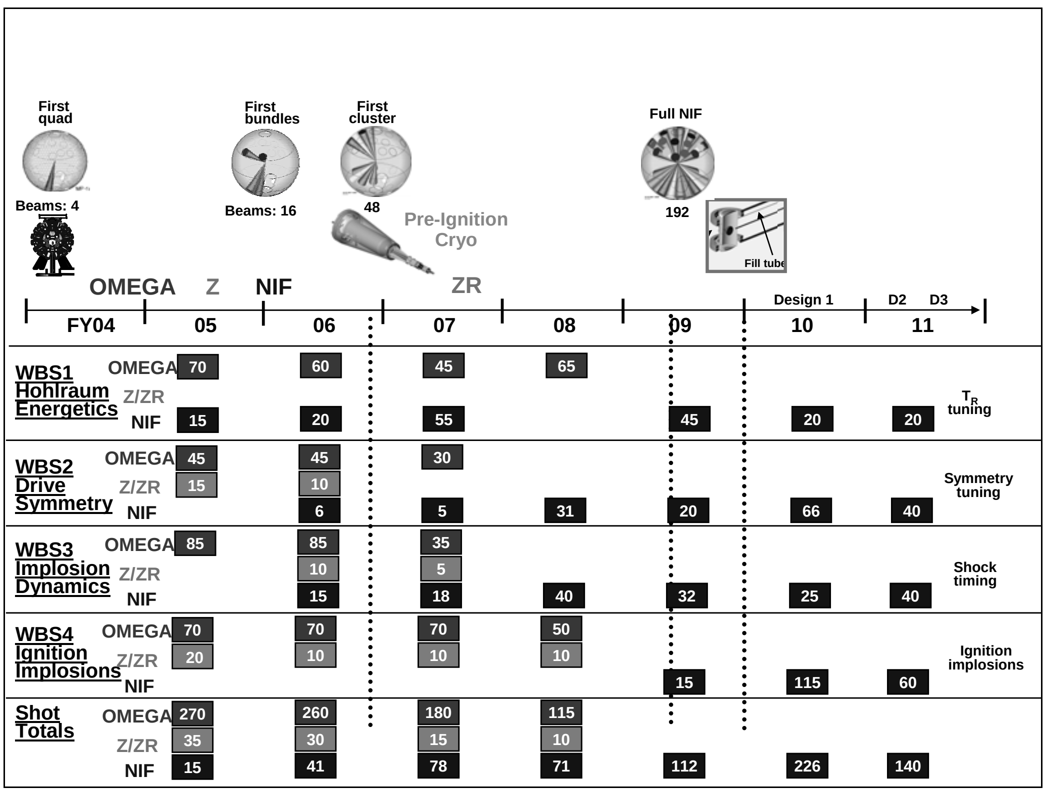



Figure 18: Robust risk reduction for indirect drive ignition requires increased focus on the national facilities for ignition attempts in 2010.

### E.3.1. Direct Drive Program

Direct drive ignition (DDI) has been considered since the inception of the ICF Program and offers the potential of higher gains (~2-3x) than indirect drive. The key facilities pursuing the DDI scheme are the OMEGA facility at University of Rochester, Laboratory for Laser Energetics, and the Naval Research Laboratory's Nike laser.

The near term work in the direct drive program involves the validation of the performance of ignition targets with symmetric laser drive. This should be completed by the end of FY 2006. (This analysis will include the implosion of ignition-scaled cryogenic DT targets, an experimental activity which was not included in the Nova technical contract series of indirect drive experiments that concluded in 1995.) A key deliverable from the direct drive program will be an assessment of the potential performance of directly driven capsules at NIF. NIF has been constructed so as not to preclude direct drive, and ultimately it is planned to demonstrate ignition on NIF in the symmetric direct drive mode. Symmetric direct drive is also a risk mitigation approach for the baseline indirect drive program.

A key component of the direct drive program is the fielding of cryogenic targets at OMEGA. The OMEGA cryogenic system represents a unique capability for the ICF Campaign, and will provide important knowledge and insight to the indirect drive cryogenic target program.

The symmetric direct drive approach would require substantial rearrangement of the baseline NIF indirect-drive beam configuration and substantial reconfiguration of the laser itself. This rearrangement and reconfiguration is estimated to cost between $100M and $400M. The NIF is being commissioned in indirect drive geometry and there are no plans to reconfigure the facility to direct drive mode before 2010. Therefore, the NIF Activation and Early Use Plan will include a small number of shots to develop the option for direct drive in which the beams can be used in the indirect drive configuration, called polar direct drive (PDD).

PDD involves beams that are not uniformly distributed around the target; i.e. the polar configuration used for indirect drive. This has the advantage that both indirect drive and PDD ignition experiments can be performed using the same beam configuration, saving the time and expense that would be incurred from switching beams to different ports. However, current proposals still involve substantial reconfiguration of the laser.

The essential elements of PDD are illustrated in Figure 19. If a target is directly illuminated with beams in the x-ray drive configuration using standard beam pointing, as shown in Figure 19(a), there would be inadequate illumination of the target equatorial region, and a high-density implosion would not be possible. Repointing of the beams, as shown in Figure 19(b), can significantly improve illumination uniformity. The optimal irradiation pattern is found by varying the beam pointing, beam spot shapes, and pulse shapes of the beams.

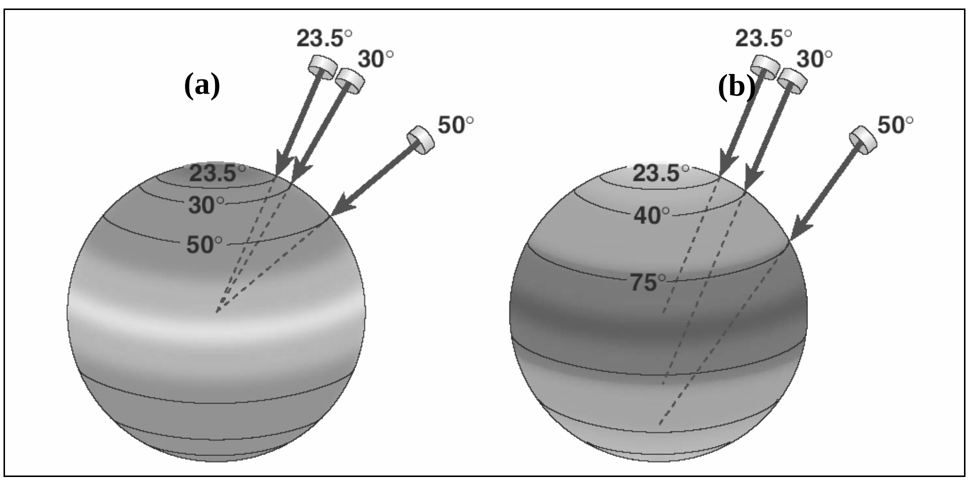



Figure 19: Characterization of the irradiation strategy required for polar direct drive: (a) Pointing beams to the target center is not adequate in the x-ray-drive configuration; (b) PDD re-points beams toward the target equator and increases intensity at the equator.

Polar direct drive, while still in its early stages of evaluation, shows some promise. For example, Figure 20 shows density and temperature contours near peak compression form a two-dimensional simulation of a NIF PDD implosion that gives a gain of

~10 (preliminary results from the University of Rochester). While review of these predictions is continuing, they are encouraging, and the program is at the point where consideration needs to be given regarding the requirements for implementing such a scheme on NIF. Initial experiments at OMEGA to test the polar direct drive scheme are underway. The fill-tube approach that was described above for indirect drive may also be applicable to direct drive targets. The requirements for the NIF modifications to accommodate polar direct drive are summarized in Figure 21. Note that these requirements have not as yet been demonstrated on a NIF-like laser beam line and planning is underway for a laser demonstration in the Omega EP facility.

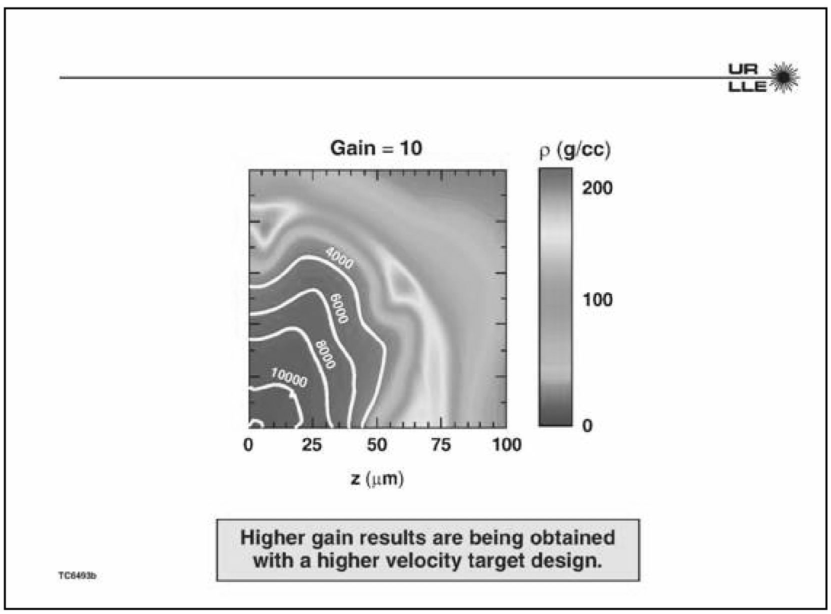



Figure 20: Beam-pointing optimization continues to improve the uniformity of target drive.

| Parameters | Requirements |
|---|---|
| Laser energy | > 1 MJ |
| Pulse shape | 50:1 contrast,<br>10-ns duration |
| Bandwidth | 1 THz, 2-D SSD<br>2 color cycles |
| Angular spread | 50 × 100 μrad |
| Polarization rotator | 50 μrad |
| Phase plates | ~3-mm-diam spot size |

TC4987e

Figure 21: Modifications to NIF required to accommodate the polar direct drive option.

## E.4 WEAPON SCIENCE: BURN PHYSICS, COMPLEX HYDRODYNAMICS, MATERIAL PROPERTIES, RADIATION TRANSPORT

### E.4.1 Introduction

As described in Appendix D, the NNSA program in HEDP includes activities in complex hydrodynamics, material properties (equation-of-state, opacity material dynamics), radiation transport, and the physics of igniting plasmas ("burn physics"). In order to be able to accurately model and have a validated predictive capability of weapon performance, it is essential to have a laboratory ability to study conditions of extreme temperature and pressure approaching those found in nuclear explosions. Key features of NIF include the ability to place macroscopic volumes of matter under the relevant high energy density conditions and to allow sufficiently precise measurements to distinguish between models and code simulations. Figure 22 illustrates the energy density conditions relevant to weapon physics and the capabilities of various ICF facilities as presented by LLNL to the task force. For the same reasons mentioned earlier for

Figure 3, the regions of phase space accessible to the various experimental facilities shown in Figure 22 are approximate, and should be viewed in the context of the significant operational differences between these facilities. For example, laser facilities, because of their advantage in power, can achieve temperatures higher than those shown for small sample sizes, whereas Z-pinches, because of their advantage in energy, can reach HEDP conditions with larger experimental samples.

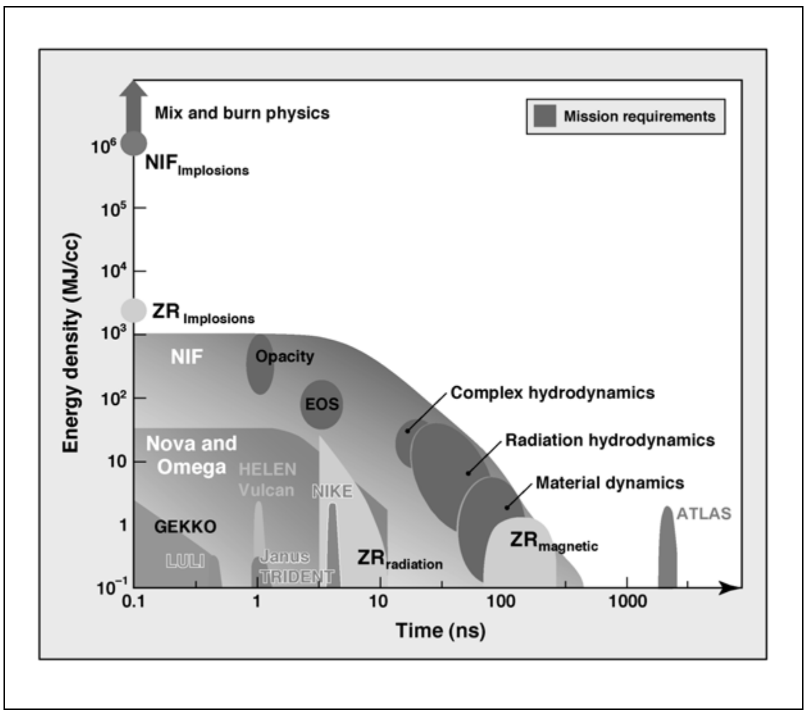



Figure 22: High Energy Density Facilities have Differing Abilities to Address Key Weapons Physics Experiments (LLNL view as presented to the task force).

In addition, NIF, like other facilities, will help develop the expertise and judgment of future stewards in areas of science relevant to the stockpile. Understanding the conditions that lead to ignition and burn of an ICF capsule will increase our confidence that we understand interactions of importance to weapons. Appendix E.3

described the NNSA program to demonstrate ignition at NIF; this will be needed to develop NIF as a platform to address burn physics issues. There are three other classes of weapon science experiments that may be performed using experimental platforms on NIF that would greatly benefit from, but do not necessarily require the demonstration of ignition. These are: complex hydrodynamics, material properties, and radiation transport.

### *Complex Hydrodynamics*

Hydrodynamics experiments are relevant to many aspects of weapon performance and outputs. Two areas of hydrodynamics where high energy density facilities can address important issues are classical fluid dynamics and instabilities, and radiative hydrodynamics, where radiation is highly coupled to the hydrodynamic phenomena. The NIF will make it possible to access a broad range of previously inaccessible hydrodynamic conditions in both planar and convergent geometry.

In addition, the high photon energy X-ray generation made possible by a new class of high energy, high intensity lasers allow the advent of a new class of diagnostics. In particular, 20 kev – 1 Mev radiography allows two-dimensional imaging at multiple times of the hydrodynamic behavior inside an implosion.

The combination of the regimes accessible, precise control of the drive, size scale and geometries accessible, along with the high energy X-ray radiographic capabilities will allow NIF to uniquely perform and diagnose experiments and acquire a completely new class of data. Hydrodynamic flows due to instabilities at material interfaces can lead to increased mixing of materials, which can have significant effects on the performance of nuclear weapons. Such experiments, in conjunction with development of advanced physics computer models, will contribute to our goal of developing and validating the next generation of three-dimensional codes. NIF has already started performing three-dimensional hydrodynamics experiments with just one quad of beams.

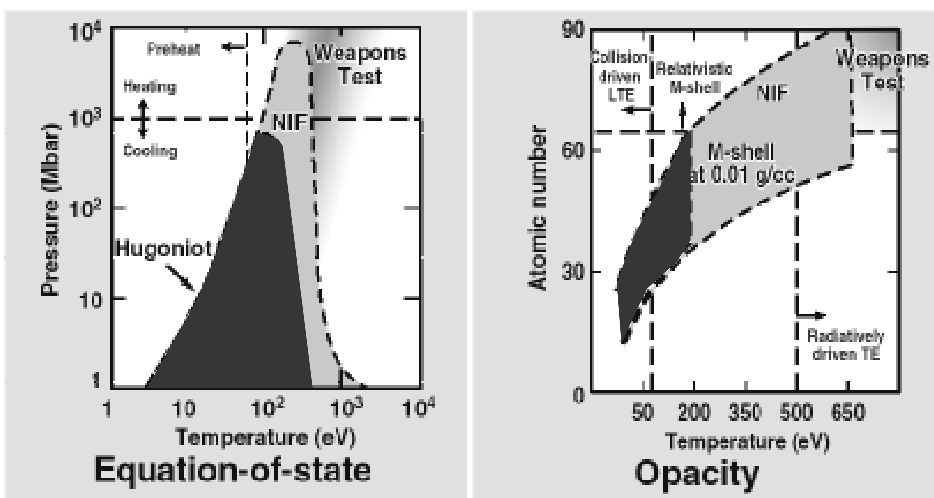
In radiative hydrodynamics, radiation generated by either a strong shock or another source couples to the evolution of the hydrodynamic phenomena and significantly modifies the evolution of the hydrodynamics. An example, relevant also to ignition, is the phenomena of ablative stabilization where Raleigh-Taylor or Richtmyer-Meshkov instability growth at an interface is reduced due to the ablation of material from the interface. NIF allows experiments in the pure hydrodynamics regime as well as with radiation. This allows additional important phenomena in weapons to be addressed.

### Material Properties

Accurate material property information is critical to the performance of the radiation hydrodynamics computer codes needed to predict the performance of nuclear weapons, and to quantify the margins and uncertainties for the stockpile. Material properties can be divided into three areas: equation-of-state, opacity and material dynamics. Data in the high pressure and high temperature regimes has been missing due to the lack of facilities that can reach the required regimes and conditions to perform precise measurements.

*Equation-of-state (EOS).* When a material is subjected to an increase in external pressure, it will compress. The relationship between the applied pressure and resultant density and temperature is described by the equation-of-state of the material. High energy density facilities are unique in their ability to achieve extremely high pressures in the laboratory. The locus of points in pressure-density space achieved by a single shock starting from room conditions is called the Hugoniot. NIF is expected to perform equation-of-state measurements from tens of MBars up to ~ GBar pressure. These extreme ultra-high pressure measurements and temperatures in regimes of interest to weapons are a unique capability of NIF and illustrated in Figure 23a. Accurate EOS input is required for every material, at every time step, and in every zone of a weapons hydrocode simulation. The complete simulation of a weapon can require EOS data over seven orders of magnitude in temperature and five orders of magnitude in density. NIF will give us access to a greater range of the relevant pressure, density, and temperature parameter space than any other above ground experimental facility allowing us to conduct experiments in regimes not previously accessible.

*Opacity.* The opacity of a material governs the absorption and transmission of x-rays in a nuclear explosive device. The absorption of radiation is a complex function of the atomic structure of the element, which in turn, is dependent on the temperature and density of the material. Of interest are the atomic systems at high enough atomic number to experience relativistic effects, and sufficient temperature and time to enable equilibrium to be reached in the experiment. Translated to experimental conditions, this demands the ionization of an element with atomic number greater than 65 to ionization states greater than 40 for several hundred picoseconds as illustrated in Figure 23b. This governs the temperature required in the experiment and the size and lifetime of the hohlraum in which it can equilibrate, plus additional power requirements for a bright x-ray backlighter. NIF is the only facility potentially capable of reaching these conditions.




(a) (b)

Figure 23: Regimes accessible on NIF of interest to weapons for equation-of-state and opacity experiments.

*Material Dynamics.* The time-resolved response of the structure of a material in the solid state under an applied stress is referred to as material dynamics. With an applied stress in one direction, the lattice structure may deform in the same direction, in a different direction, or uniformly, for example. In addition, the lattice can undergo a solid-solid phase transition with a resultant change in density, or melt. These changes will affect the density under compression (e.g.

equation-of-state), as well as the mechanical properties (e.g. material strength) and ultimately the hydrodynamic behavior of the material. Data is required in high pressure regimes where materials are in the solid state to validate the models used in codes. These complex multi-scale models require a combination of quantum mechanics, statistical physics of a large but finite number of lattice points or grains, and continuum dynamics to follow material deformation. The advent of facilities that can reach these conditions coupled with a set of X-ray diagnostic capabilities to measure the dynamic evolution of material response has created a new area of research using high energy density facilities. NIF is unique in the potential capability to reach tens of MBars of pressure in materials in the solid state over a varying strain rate to perform equation-of-state and strength experiments. Figure 24 illustrates the range of accessible conditions on NIF for quasi-isentropic compression of materials.

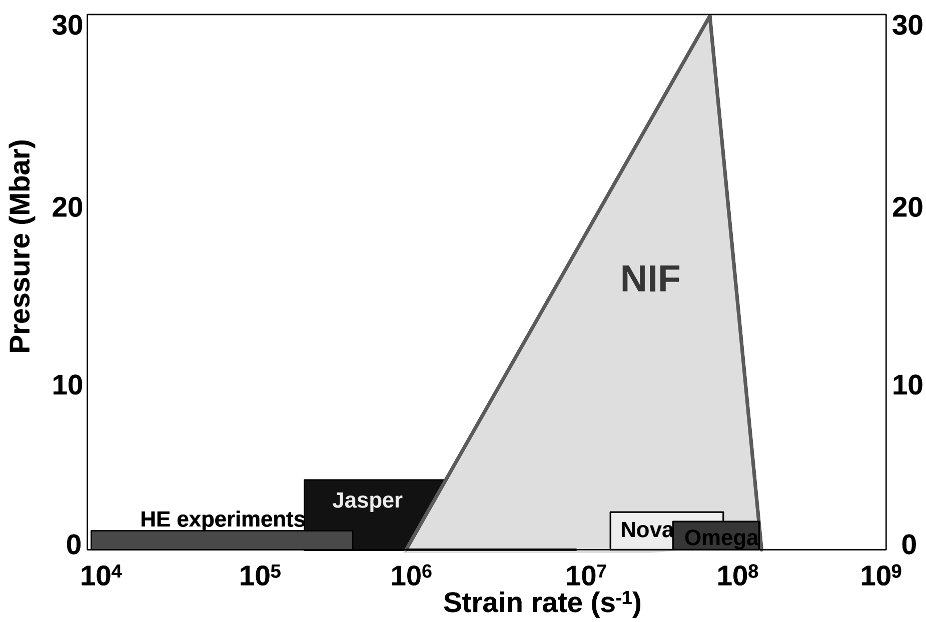



Figure 24: Range of conditions accessible on NIF for material dynamics experiments

### *Radiation Transport*

The propagation of radiation through and from the weapon is a fundamental issue to performance and outputs. Present radiation transport models generally do not include exact treatments, and must rely on simplifications and approximations. In addition, conditions of interest are often highly dynamic and involve the interaction of radiation with other phenomena such as hydrodynamics and material properties. Experiments are required to validate the codes under these dynamic conditions and integral physical phenomena. The NIF allows such transport experiments to be executed in an integral fashion both in static and dynamic conditions, with different geometries and with sufficiently detailed diagnostics to allow the ability to simultaneously validate different aspects of the code.

The major milestones for the weapon science portion of the NIF Activation and Early Use Plan are shown in Figure 5. The timing of these milestones is based on two major factors: programmatic need and optimization of the overall integrated facility schedule.

Programmatic need for the experiments discussed in this section is determined largely via quantitative analysis of stockpile performance margins and uncertainties. The formal process in this area is known as Quantification of Margins and Uncertainties (QMU). The weapon laboratories have developed QMU over the past several years. The goal of QMU is the quantification of uncertainty and performance margin associated with specific weapon issues. QMU can be used to prioritize the HEDP weapon science program, with higher priority placed on issues having larger impacts on performance margin. The JASON group is currently conducting a separate review of QMU. The relative priorities based on this analysis by LLNL is shown in Figure 25. LANL has performed a similar analysis and have reached a similar set of conclusions, differing in a few specifics.

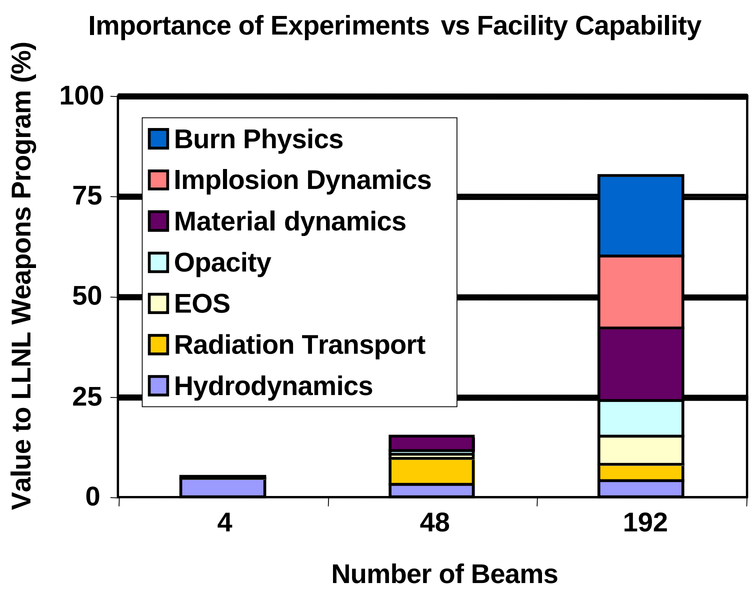



Figure 25: Importance of experiments in support of the LLNL weapons program

This prioritization coupled to the implementation of the NIF Project leads to the milestone plan in these areas as shown in Figure 26 as jointly developed by LANL and LLNL.

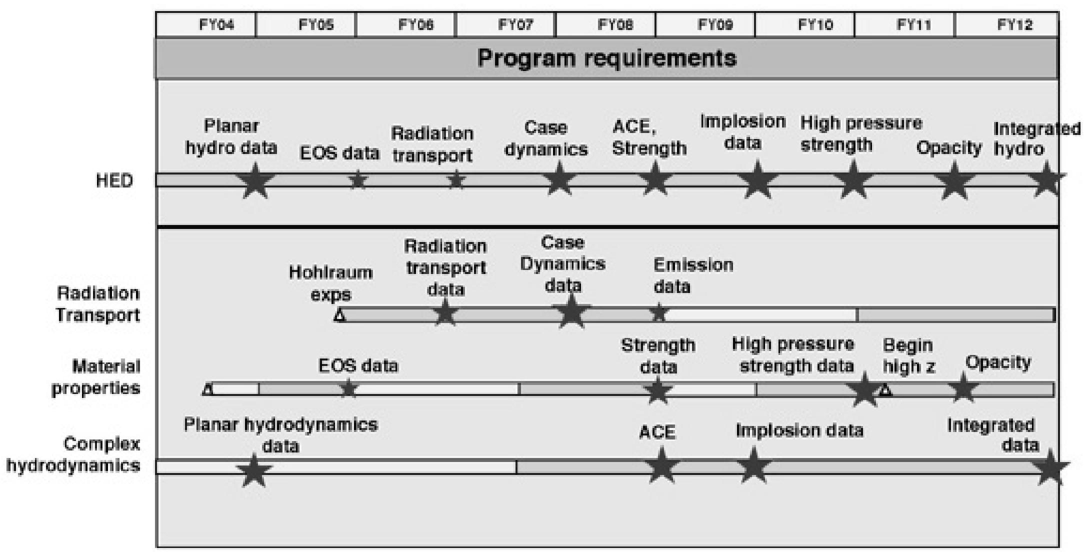



Figure 26: Breakdown of NIF milestones in experimental areas thru FY12

Figure 27 summarizes the planned LLNL and LANL weapon science activities at NIF as described to the task force. Experiments requiring ignition and the NIF Advanced Radiographic Capability (ARC) are indicated. (ARC will be discussed later in this section.) Again, note there is no community consensus about modifying NIF for ARC capability before it is completed in FY09. While the set of milestones is separate, LLNL and LANL have worked closely to ensure their plans are coordinated with facility capabilities. Such joint planning is essential to producing an experimental program consistent with the expected NNSA budget.

| Experiments Have Been Designed to Address | NIF Experiment Start Date | Requires Ignition | Requires ARC |
|---|---|---|---|
| Jets and jet interactions | FY04 | | |
| Equation of State | FY05 | | |
| Radiation transport | FY06 | | |
| Radiation hydrodynamics | FY07 | | ✓ |
| High Pressure Material Properties | FY07 | | ✓ |
| Implosion Hydrodynamics | FY09 | | ✓ |
| Opacities | FY10 | | ✓ |
| Boost Physics | FY10 | ✓ | ✓ |
| Burn Physics | FY10 | ✓ | ✓ |

Figure 27: LLNL and LANL Weapon Science Activities Planned for NIF

While programmatic needs for weapon science are set by LLNL and LANL, the program in this area is national in nature. To effectively execute an experiment, four categories of activities are required: development of the experimental conditions, resolution of outstanding target physics issues required to quantitatively compare with models or codes, development of the measurement techniques, diagnostic and calibration facilities, and development of the target fabrication processes, characterization and targets. This is shown in Figure 28. Research and development in these areas at facilities such as OMEGA and Z in a national program are critical to the success of the overall HEDP weapon science program.

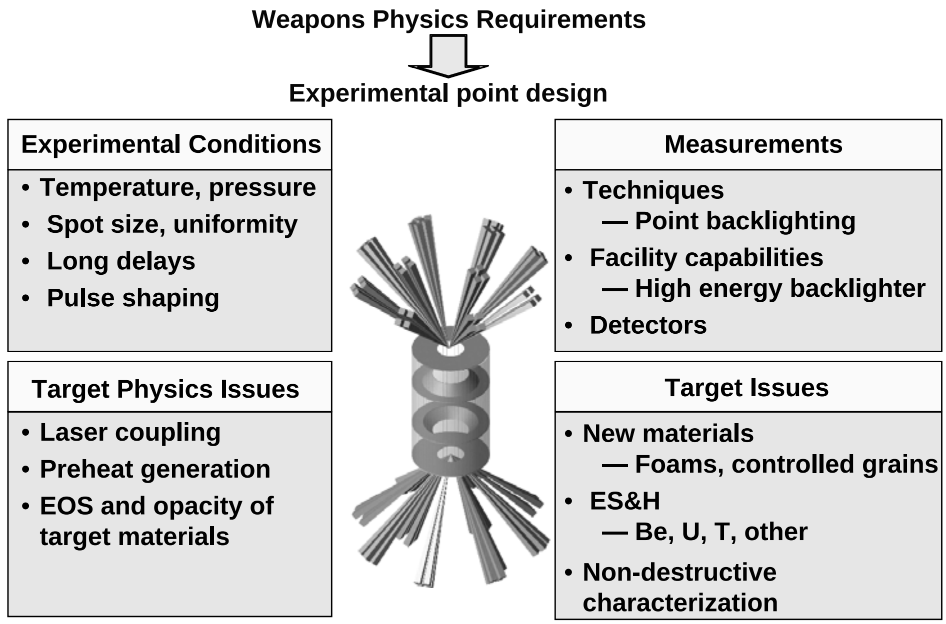



Figure 28: Required capabilities to execute an experiment.

### E.4.2 "Platforms" for NIF experiments

Because of the broad spectrum of important experiments capable on the NIF, there is a need for a broad range of different capabilities. A key factor in planning for NIF weapon science experiments is the use of a minimum number of stable, well-characterized plasma environments. These environments are known as "platforms." A platform will typically consist of a specific laser configuration, a radiation environment ("hohlraum") produced by the laser-hohlraum interaction, a target to be irradiated within the hohlraum, and experimental diagnostics. For weapon science the number of possible laser, hohlraum, target, and diagnostic configurations is large. From past experience on many facilities, the majority of time and effort on an experiment is usually devoted to characterizing the platform. Thus minimizing the amount of differing platforms needed is highly desirable. Minimization of the number of platforms is a key strategy in the NIF Activation and Early Use Plan.

An example of a platform is shown in Figure 29. This platform was commissioned in FY04 and was used in experiments to satisfy a FY04 NNSA level 1 milestone. This figure points out some of the key factors considered in planning for NIF weapon science experiments, which are summarized below.

*Diffractive optics:* Optics known as "phase plates" are placed near the NIF final focus lens and used to produce focal spots of the desired size and quality. A single phase plate must be produced for each NIF beam. The overall plan for procurement of phase plates is discussed in Sec. E.5.

*Diagnostics:* Specific diagnostics are required for each weapon science experiment. The integrated diagnostics schedule is discussed in Sec. E.5. Figure 30 shows the integrated diagnostic set for weapon science experiments.

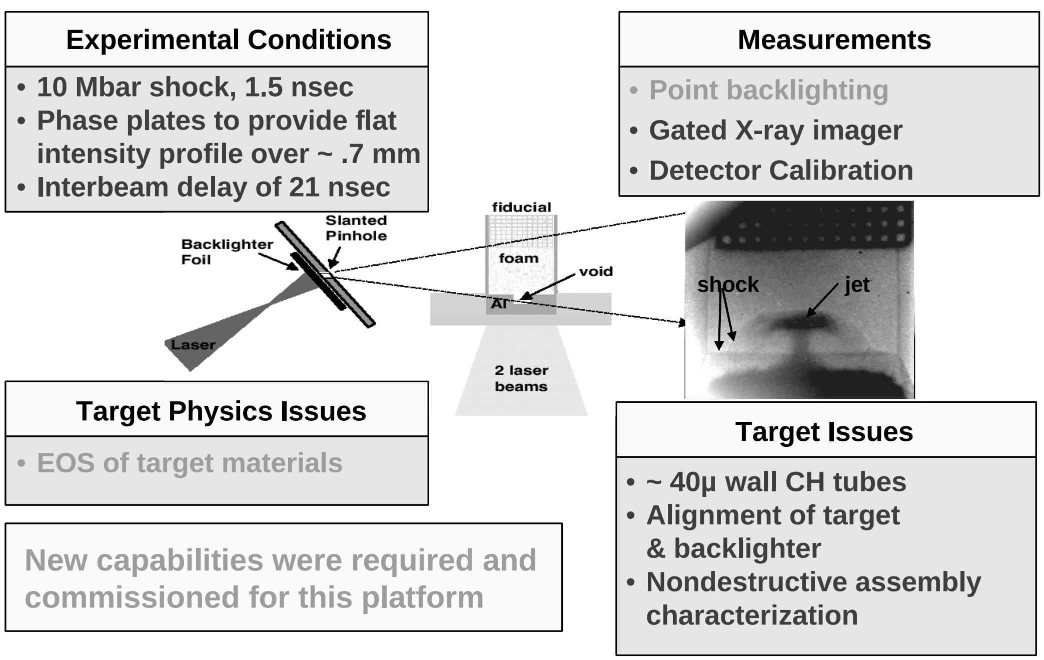



Figure 29: A Hydrodynamics Platform was Commissioned this Year on NIF.

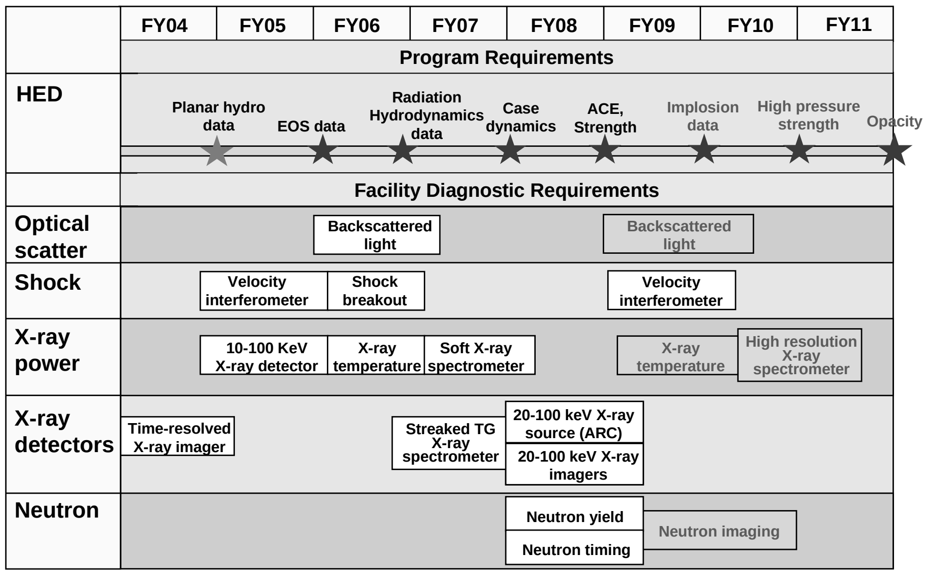



Figure 30: Timetable for diagnostics required to support the weapons science experiments on NIF

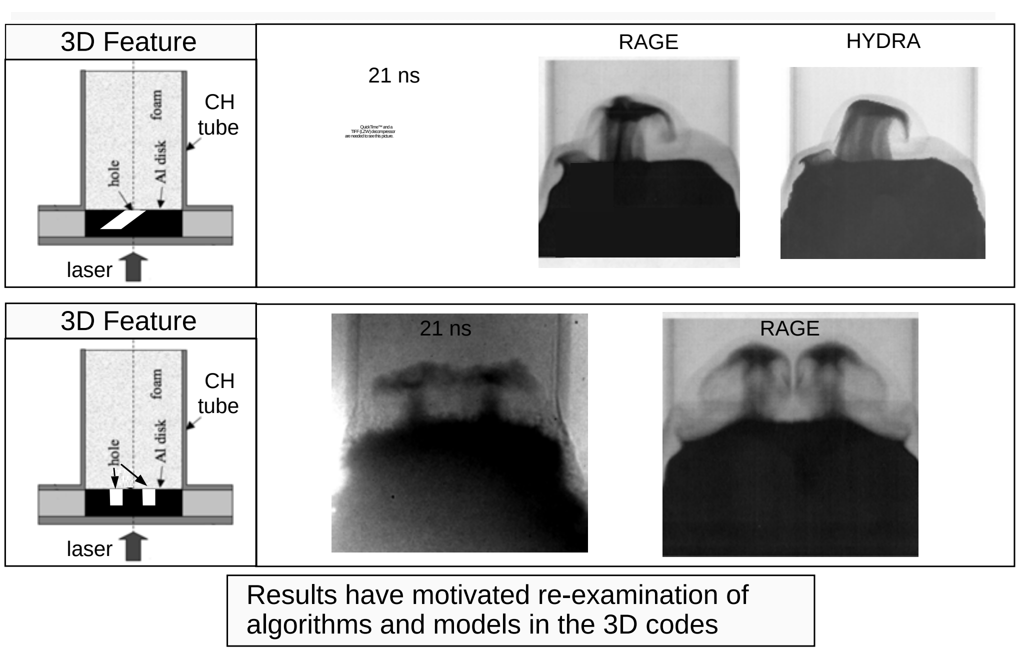



Figure 31: Once developed, the Same Platform can be used to Perform Different Experiments.

The NIF ARC, shown as one of the x-ray detector diagnostics in Figure 30, involves the addition of equipment to allow a 1-10 picosecond, one kilojoule pulses from a NIF beam. This short-pulse beam generates x-rays used for absorption diagnosis of NIF targets. The short-pulse beam is needed because of its unique ability to produce the 10-50 keV x-rays that are optimal for target backlighting.

*Target fabrication:* Advanced targets must be developed for each specific experiment. Target fabrication plans for both weapon science and ignition are covered in Sec. E.6.

Figure 31 show how this platform, once it is developed, can be used for performing additional complex experiments. In the figure, three-dimensional and multi-jet experimental results from initial NIF experiments (NIF Early Light [NEL]) are shown along with LANL and LLNL code predictions. The differences between the simulation codes and experimental data as shown in Figure 31 are under investigation.

An example of the national nature of platform development is shown in Figure 32 where results from various laboratories regarding the EOS of deuterium are shown. Various theoretical models for this equation-of-state have been proposed which vary significantly in their predictions. Determination of an accurate equation-of-state for this basic material is essential for stockpile stewardship and a needed next step in equation of state research. The ability to examine this question with differing platforms (in this case Nova, OMEGA, Z, and Nike as facilities and impedance match vs. radiography) has been a key component to making progress on this issue.

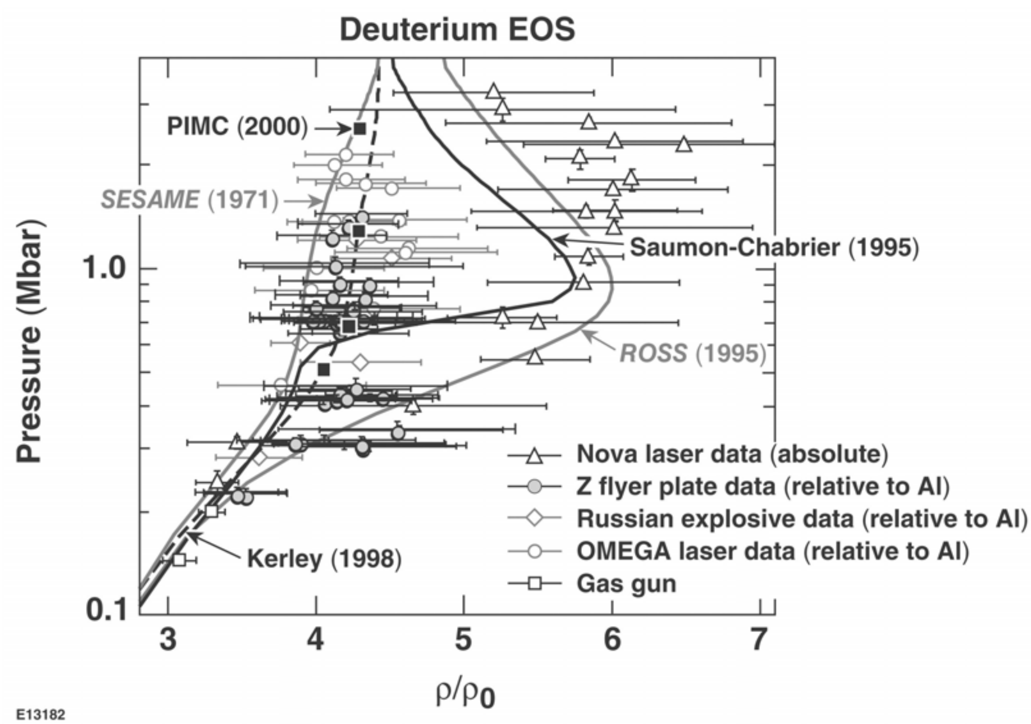



Figure 32: Results from various laboratories regarding the equation of state of deuterium are shown (data are shown by the points and different theoretical models by the lines).

### E.4.3 Advanced Radiographic Capability

The advent of a new class of high-energy, high-intensity lasers has created the potential of a high fluence of high photon energy X-rays and protons as diagnostic probes or for heating of compressed matter. This new diagnostic capability is referred to above as the Advanced Radiographic Capability (ARC). As described in Figure 27, experiments are now planned to use this capability on NIF. Radiography at photon energies in the range 10 keV to 1 MeV, using a single beam of NIF can replace the techniques previously envisioned, such as using ~30 beams which would achieve ~20 keV radiography. The benefits include up to 1000 times more penetration through matter and 10-fold reduction of motion blurring through shorter pulse length. A quasi-continuum backlighter source for opacity experiments is greatly simplified with the ARC. Pulsed diffraction measurements of crystal structure changes under high stresses will be much extended in capability using higher energy K-alpha photons. Proton beams offer a novel complementary radiography with micron resolution capability and sensitivity also to electric and magnetic fields through deflectometry. A summary of the applications of ARC is shown in Figure 33.

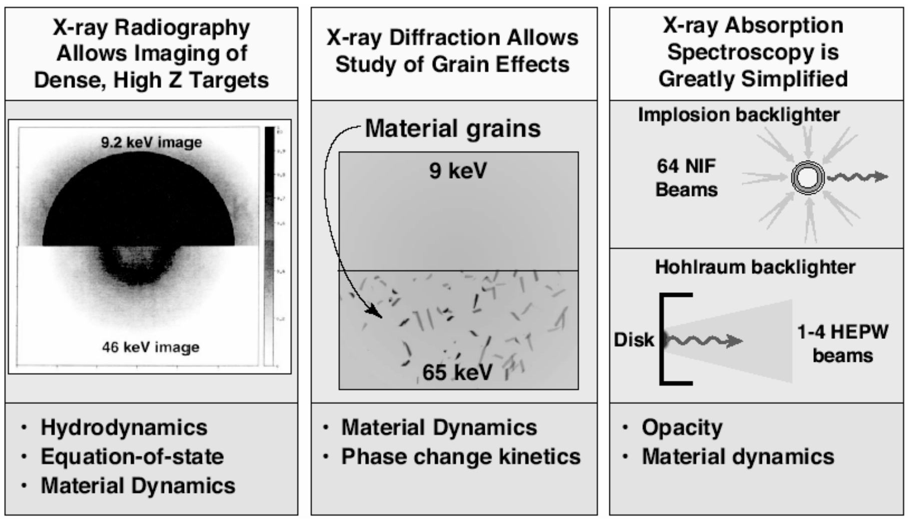



Figure 33: Applications of ARC as a high energy diagnostic probe

Another potential powerful application of the ARC to weapons science experiments lies in its ability to decouple the compression effect from the heating effect in an experiment. Typically on an HED facility, the drive is used to provide both compression and heating of the target. The relationship of the amount of compression to heating is restricted to certain regimes, depending on the experiment. With an ARC, the main laser can be used to compress and the ARC can be used to provide heating, via energy deposition using electrons or protons. This allows, for example, a wider space to be accessed for equation-of-state experiments. The conditions achievable for NIF as shown in Figure 23a for equation-of-state is now greatly expanded beyond that shown in the figure.

### E.4.4 Integrated Planning Example: Case dynamics

An example for the integrated planning required to execute an experiment is described in this section. Starting from the requirements, a point design of an experiment is generated, which describes the platform, associated issues that need resolution and capabilities that are required such as shown in Figure 34. A detailed schedule is then assembled identifying when these activities are required to be completed. Integrated plans for the experiments have been assembled. These plans include the platform issues discussed in Sec. E.4.2 as well as experiments at OMEGA, Z, and other facilities. An example of the integrated plan for one such area, case performance, is shown in Figure 34. This plan culminates in completion of the FY2007 "Case dynamics" milestone shown in Fig. 5 earlier.

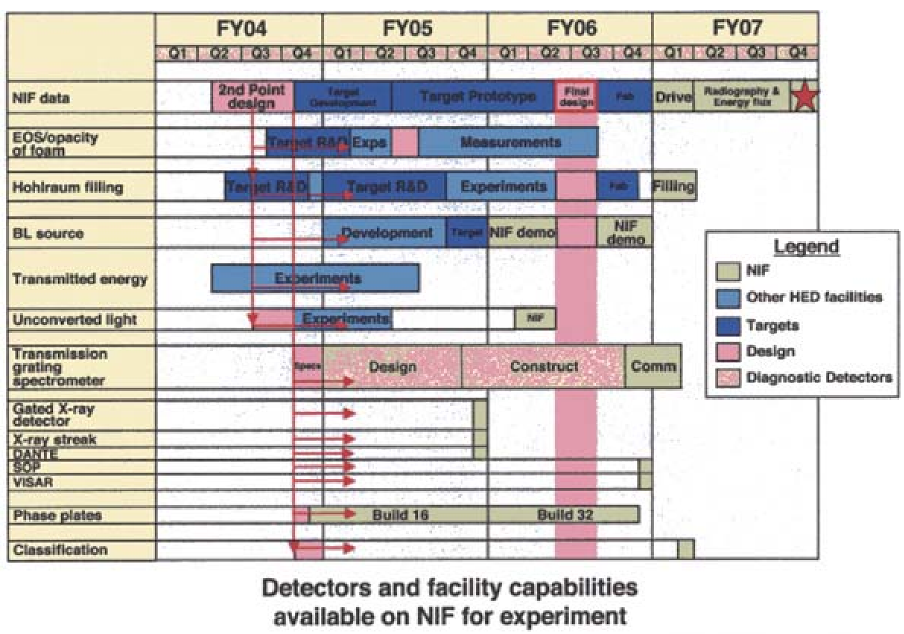



Figure 34: The Plan Requires Integration of Experiments, Diagnostics, Target Development, and Facility Capabilities.

Figure 34 shows that a number of target physics, diagnostic, facility, and other issues must be addressed in order to achieve the FY07 milestone shown in Figure 5. Note that 48 phase plates must be procured by the end of FY06. Required diagnostics must also be in place by this time. Experiments to address hohlraum filling, equation of state, and other issues will be carried out at other HEDP facilities to support the planned FY07 case performance campaign.

### E.4.5 Risks

An assessment of risks to execute the weapons science plan was performed. A summary is shown in Figure 35. For each milestone, risks were assessed in the four areas of achieving the experimental conditions, resolution of associated target physics issues, making the required measurements at the requisite accuracy, and producing the required targets. Low risk is defined to have been previously demonstrated or not critical to the success of the experiment. Medium risk is defined to require straightforward extrapolations, data that is straightforward to acquire or having multiple methods to achieve the requirements. High risk is defined to be very difficult, never been demonstrated issues. The risks in the stockpile science on NIF are low to medium through FY09 and medium to high FY10 and beyond. Experiments in FY12 and beyond will require significant research and development.

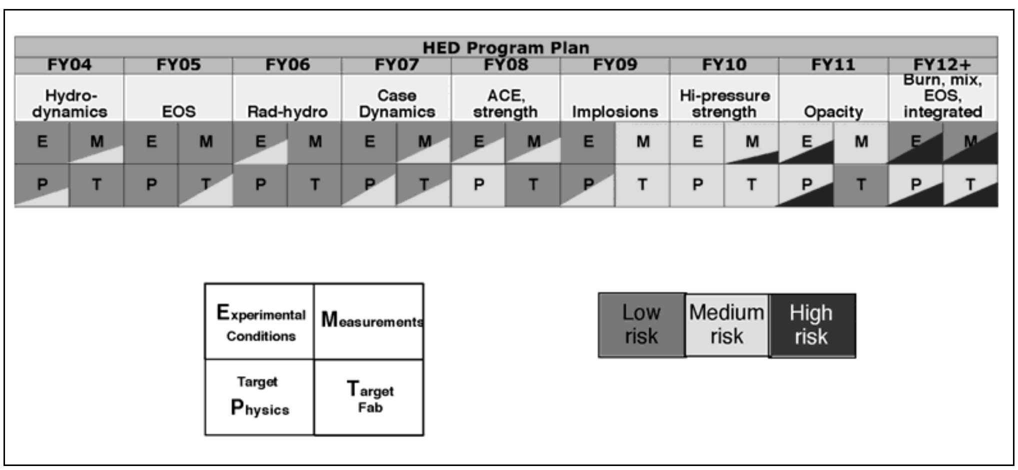



Figure 35: Risks associated with meeting the weapons science milestones on NIF

Included in the development plan is the research and development required to mitigate the risks. An example is the area of target fabrication. While each experiment has specific requirements for targets, there are cross cutting technologies that impact all the experiments. New materials or fabrication technologies can provide enhanced or required capabilities. Figure 36 highlights the impact of new materials or technologies in these areas on all the program, milestones.

| | | FY07 | FY08 | FY09 | FY10 | FY11 | FY12+ |
|---|---|---|---|---|---|---|---|
| | Impact of new target capabilities | Case dynamics | Strength | Implosions | High pressure strength | Opacity | Burn, mix |
| New materials | Metal foams | Enhanced capability | | Required | | Enhanced capability | Required |
| | Graded-density foams | | Enhanced capability | Risk reduction | Required | | Required |
| | Controlled Grain size | | Enhanced capability | | | | Required |
| 3D Fab | Fast tool servo; coining; lithography | | Risk reduction | Enhanced capability | | | Enhanced capability |
| | Precision micro-assembly and characterization | Risk reduction | | Required | | | Required |

Low Risk / Medium Risk / High Risk

Figure 36: Impact of new target fabrication capabilities on program requirements

## E.5 NIF EXPERIMENTAL SUPPORTING TECHNOLOGIES

The NIF Experiment Support Technology (EST) Program builds and commissions the experimental systems needed to field successful experiments at the facility. It includes the areas shown in Figure 37.

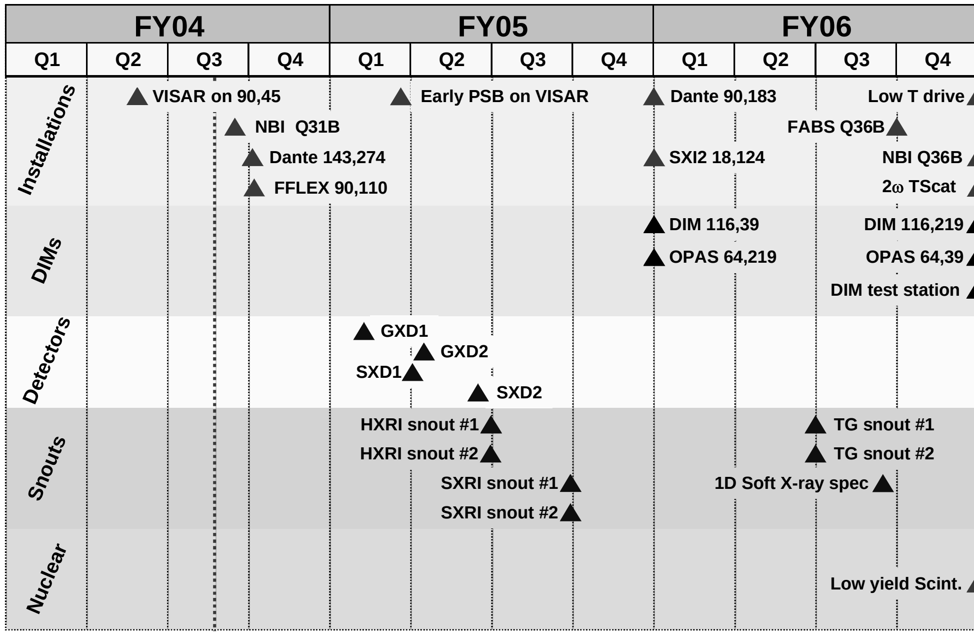
| | |
|---|---|
| Target Diagnostics | Design, engineer, construct, and commission the diagnostics and diagnostic manipulators |
| Target Area Support Systems | Provide diagnostic integration, diagnostic alignment systems, environmental protection systems, and data archive systems |
| Target Area Operations | Assemble, commission and operate systems in the target area, including positioners (Target Positioner, Target Alignment Sensor Positioner, Diagnostic Instrument Manipulators, SXI) |
| NIF Cryogenic Target System | Design, engineer, construct, and commission the equipment to fill, deliver, support and characterize cryogenic targets |
| User Optics | Develop the design and fabrication techniques, and identify industrial vendors to produce hundreds of large optics necessary to shape the laser beams as they illuminate the target and protect the final optics from target debris. |
| NIF User Support Office | Staff an office to manage NIF governance and provide user support. |

Figure 37: NIF Experimental Support Technology

The systems described in Figure 37 are necessary to field increasingly more sophisticated experiments on NIF leading up to ignition. Ongoing innovation in these disciplines and changing needs of Stockpile Stewardship will continue the need to invest in these areas indefinitely into the future. Description of major activities in these area follow below.

*Target Diagnostics:* Diagnostic engineering, installation, and commissioning is a collaborative effort among the ICF/HEDP stakeholder laboratories. This program is supporting the construction of about 30 target diagnostics and manipulators comprised of imaging systems, spectrometers, detectors, and manipulators. As shown in Figure 38, these are planned to enable the key experiments that are consistent with the evolving experimental capability of NIF.

As new technology is developed the program will also be responsible for engineering and integrating new diagnostics and upgrades to existing systems. The goal is to provide a standard set of diagnostics for all NIF users. A number of important diagnostics, such as the gated x-ray imager, streaked x-ray imager, and Velocity Interferometer System for Any Reflector velocity interferometer, have already been commissioned on NIF, and installation of others, such as the Dante soft x-ray drive diagnostic and the Filtered Fluorescer Spectrometer hard x-ray spectrometer, are well underway. The diagnostic systems that will eventually be installed on the NIF were chosen based on a set of requirements developed by representatives of the ICF, HEDP, and Nuclear Weapons Effects Test communities.




***Date represents system ready for commissioning tests (CTP)***

Figure 38: Three-year diagnostic schedule, FY04-FY06

*User Optics:* The NIF laser beams have remarkable precision when focused to the center of the target chamber. In order to match the beam size at focus to the experimental requirements of size and shape, a special optic is inserted in the laser beam path. These so called "phase plates" produce the required focal spot shaping. For NIF, these optics are 40 cm square and one or more per beam line are required for most experiments. The NIF EST Program develops the necessary phase plate designs, develops the manufacturing techniques, puts in place the industrial manufacturing capability, and buys the phase plates consistent with experimental needs.

Another category of user optics is debris shields. These shields are thin optics adjacent to the target chamber that intercepts the debris produced when the laser beams hit their targets. The debris shields protect the high value final optics. NIF will have two debris shields in series. The first is a long-lived optic that can be refurbished. A second very-thin disposable debris shield is used closest to the target. It will be used for up to ten target shots and then moved out of the way and eventually disposed of. NIF EST pays for the design of these systems; the development of the vendor base necessary to manufacture the debris shields and for the debris shields required by experimentation on NIF.

*NIF Cryogenic Target Systems:* The NIF Cryogenic Target System (NCTS) is another important element of NIF EST. This system provides the equipment and procedures to fill, cool down to near absolute zero in temperature, layer, characterize, and deliver the target to the center of the target chamber while maintaining its temperature and stability specifications. These systems are required to field a fusion target.

Current plans call for an NCTS ignition system to be deployed in two phases (in addition there is a simple system to handle non-ignition targets). The two phases involve deploying a warm-transport system for ignition targets designed with fill tubes, or for capsules with sufficient strength to withstand the pressure, and a diffusion fill and cold-transport ignition system that will accommodate plastic capsules that don't require fill tubes. These deployments build on the previous system and increase the versatility of the system and their complexity.

The initial non-ignition cryogenic capability will be ready for experiments at the time the first cluster (48 of 192 beams) of laser beams is operational in NIF. The phase 1 ignition cryogenic target system is now in conceptual design, and will be available in late FY09. The third phased system will be available after 2012. The plan for the phased NCTS is shown in Figure 39.

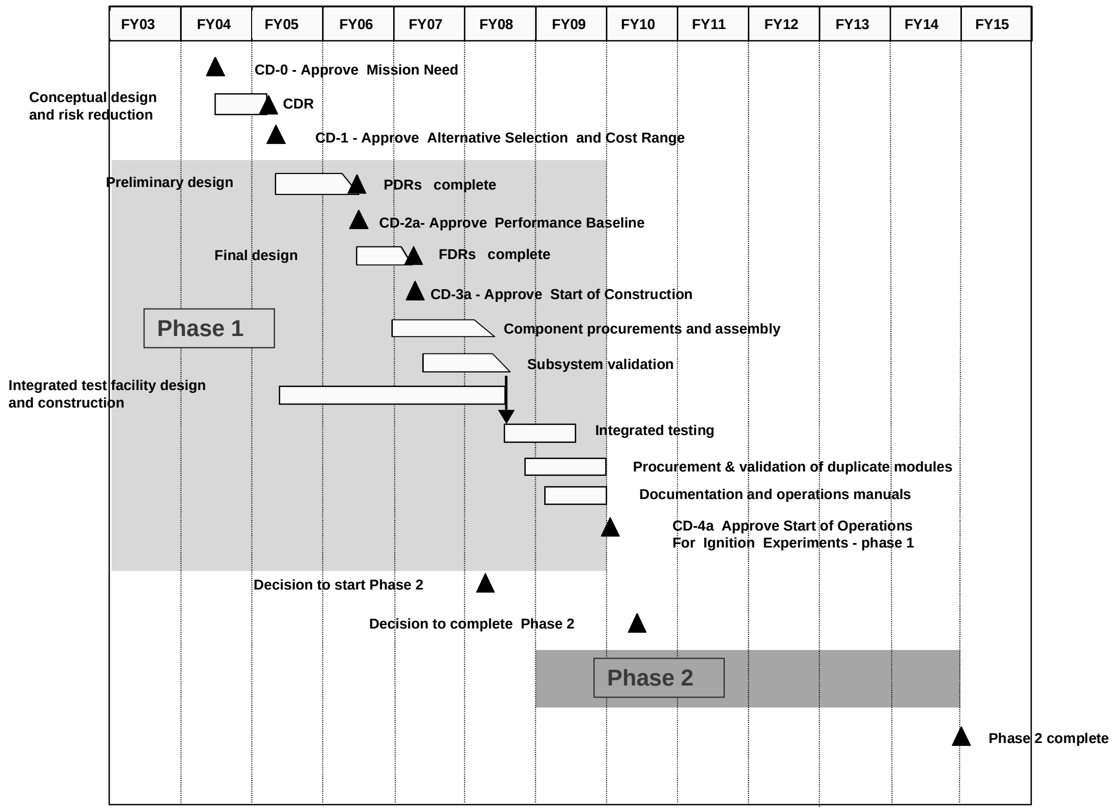



Figure 39: Preliminary Schedule for NCTS

## E.6 TARGET DEVELOPMENT

General Atomics Corporation (GA) serves as NNSA's ICF target support contractor, providing target development and fabrication and target system engineering development. Significant target research and development work also takes place at the weapons laboratories and other ICF program elements.

The targets to be used in the first ignition experiments on the NIF will be indirect drive (ID) targets, similar to the one shown in Figure 12. There are similarities in most ignition target designs for the NIF. They are usually hollow, with an outer layer of low-Z material, such as beryllium or a permeable polymer (Carbon-hydrogen) usually referred to as "plastic." Inside the outer layer is another layer of solid deuterium-tritium (DT) fuel material. The hollow center of the target is filled with gaseous DT. The baseline NIF ignition target is a beryllium target. The current target research and development program is focused on a number of remaining key issues that reflect this choice of target material. For example, they include improving Be surface roughness and bulk morphology, and improving Be strength. Plastic targets can be filled via diffusion of DT through the outer layer. This method will not work for beryllium targets, which will require a fill hole to pass the DT fuel through the beryllium outer layer. Other key issues for research and development are, therefore, minimizing the fill tube size and joint, and the development of laser sealing for a possible drill and plug target fielding method.

In addition to the ignition targets described above, a great variety of other types of targets will eventually be fielded on NIF to explore areas of high energy density physics of interest to the stockpile stewardship program. For example, planar targets will be needed to study EOS, hydrodynamic instabilities and shock physics. Other targets will serve in conjunction with backlighter laser beams as x-ray sources. Modified hohlraum targets, sometimes referred to as "halfraums," will be used to study laser/plasma interactions and a variety of other phenomena.

Significant enhancement of our target production infrastructure will be needed to provide the number and variety of targets that will eventually be needed on NIF. In the past, target production has been focused on one-of-a-kind items. This mode of production will, no doubt, still be needed for some experimental applications. However, by 2010 we will also need about 100 ignition targets per year. A national production plan for x-ray drive ignition targets is being developed that will allow us to meet or exceed this goal by 2009. The plan calls for building on the extensive national target production infrastructure already in existence. GA, for example, already produces thousands of targets and components for other facilities annually. Eventually, different target components will be produced at several sites, including GA, LLNL, and LANL, and assembly of the targets will take place at LLNL.

## E.7 UNIVERSITY ACTIVITIES

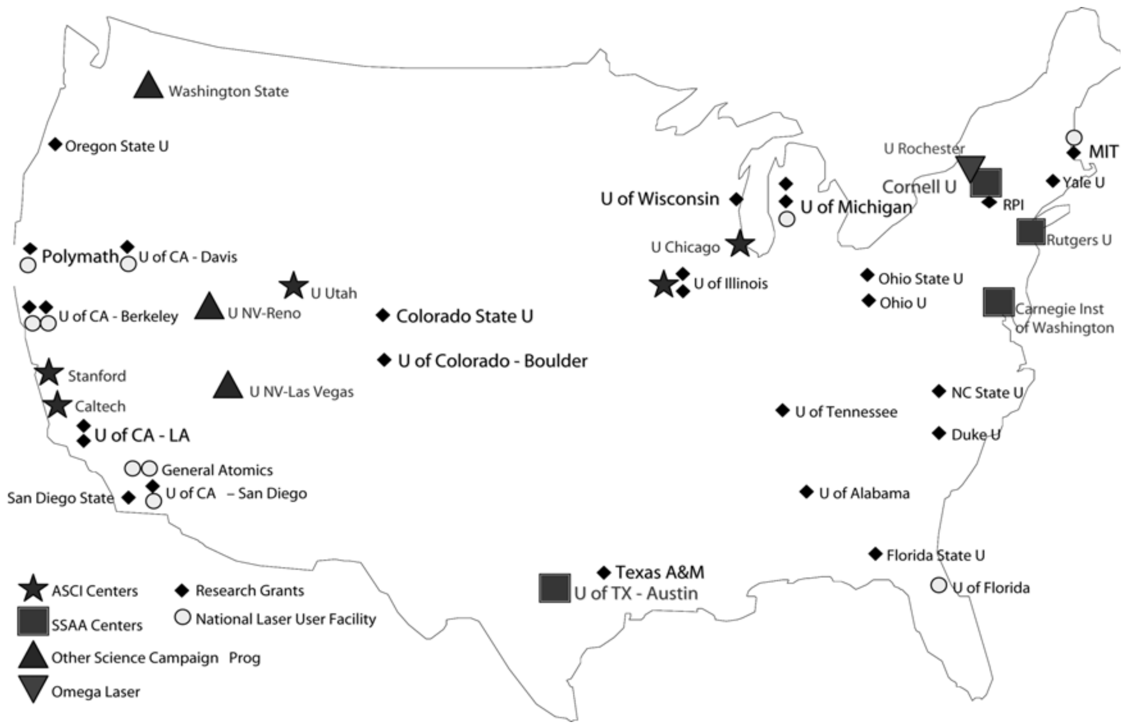



Figure 40: NNSA sponsors university research in a variety of technical areas.

NNSA supports a range of university activities in high-energy-density physics and other areas. These activities support strategic goal #4 of the ICF Campaign. There are currently two academic grant programs closely related to the use of NNSA ICF facilities: the National Laser User Facility (NLUF) grant program and the Stewardship Science Academic Alliances program (SSAA). Both these programs are managed by DOE/NNSA. Figure 40 shows the location of all SSAA activities.

The objective of the NLUF program is to make NNSA's OMEGA laser at UR/LLE accessible to a broad community of academic and industrial research interests. NLUF presently funds nine academic users to perform a total of 4 weeks per year of shot time on OMEGA. Total NLUF program funding is $1M per year.

The objectives of the Stewardship Science Academic Alliances Program are to:

1. Grow the U.S. scientific community, through the funding of research projects at universities, in areas of fundamental science and technology relevant to stockpile stewardship, with a focus on those areas that have not been traditionally supported by other federal agencies and for which there is a recruiting need within the NNSA/DP laboratories complex;

2. Provide fundamental-science information and develop advanced experimental measurement techniques in selected areas of physical sciences: condensed matter physics and materials science, hydrodynamics, plasma and high-energy-density physics, fluid dynamics, and low-energy nuclear science;

3. Train scientists in specific areas of research relevant to stockpile stewardship;

4. Promote and sustain scientific interactions between the academic community and scientists at the NNSA/DP laboratories through exchange of personnel;

5. Increase the availability of unique experimental facilities sited at the NNSA/DP laboratories to the academic community, particularly for collaborations in areas of relevance to stockpile stewardship;

6. Develop and maintain a long-term recruiting pipeline to the NNSA/DP laboratories by increasing the visibility of the NNSA/DP scientific activities to the U.S. faculty and student communities; and

7. Complement the current NNSA/DP Accelerated Strategic Computing Initiative (ASCI) Academic Strategic Alliances Program (ASAP) supporting the Strategic Alliance Centers of Excellence by emphasizing primarily experimental research in forefront scientific areas aligned with the NNSA/DP mission needs.

SSAA funding is approximately $13M per year, with approximately $6M per year going to high-energy-density physics.

Awards range from single investigators (order of $100-200K per year) to centers of excellence (up to $2M per year).

The NNSA ICF Campaign facilities represent a unique resource for basic high-energy-density physics. The relative importance of high-energy-density physics as a scientific field has been recognized in two recent National Academy of Science reports.[2] Key technical areas in which there are major scientific opportunities include:

- High energy density laboratory plasmas
- High energy density astrophysics
- Laser-plasma and beam-plasma interactions

These reports urge the enhancement of existing increased attention to the field by the various funding agencies. Additional funds for university activities and user programs at major NNSA facilities are also recommended.

Interagency coordination in the field of high-energy-density physics is accomplished via the Interagency Working Group on the Physics of the Universe. This group has recently published a report[3] recommending that a national "roadmap" for high-energy-density physics be produced. This "roadmap" document has been generated and will help guide agency decisions regarding future activities in high-energy-density physics.

With NIF coming on line, it is appropriate that additional resources be devoted to university research, including use of major facilities. NNSA is examining university programs and user facility policies and assembling a plan for enhanced university activity in the high-energy-density physics area. Preliminary recommendations are expected shortly that will help guide budget decisions for the FY06-10 timeframe. Final decisions will be incorporated into the NIF Activation and Early Use Plan.

2. *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (National Academies Press, Washington, DC, 2003); *High Energy Density Physics: The X-Games of Contemporary Science* (National Academies Press, Washington, DC, 2003)
3. *A 21st Century Frontier for Discovery-The Physics of the Universe: A Strategic Plan for Research at the Intersection of Physics and Astronomy*, National Science and Technology Council, Committee on Science, 2004.

## E.8 SUMMARY OF NIF INTEGRATED PROGRAM

The NIF Activation and Early Use Plan requires that experimental activities be integrated with the completion of the project, the user experimental requirements, and the diagnostic requirements and other facility capabilities.

As noted previously, the original NIF user requests exceeded available resources by approximately a factor of two. Reduction in the number of platforms and a prioritization process were used to reduce overall user demands. Figure 41 summarizes at a high level the set of activities proposed for the NIF Activation and Early Use Program.

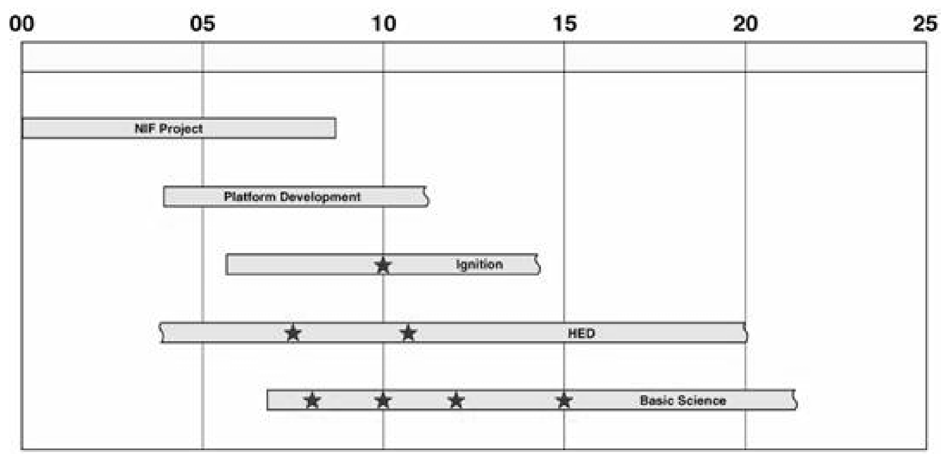



Figure 41: Schedule – NIF Activation and Early Use Plan activities.

The Weapons Physics plan focuses on a few experiments and a few major activities, with a single milestone each year. The highest priority weapon science needs of LLNL and LANL have been incorporated into the program. Results of these experiments will be used to validate calculations of performance margins and uncertainties. Many of the experiments are chosen by the degree to which they contribute to reduction of uncertainties on key issues related to nuclear weapons performance. The milestones for the ignition and weapons physics plans have been matched to NIF capabilities and resources.

Figure 42 summarizes the milestones for the campaigns.

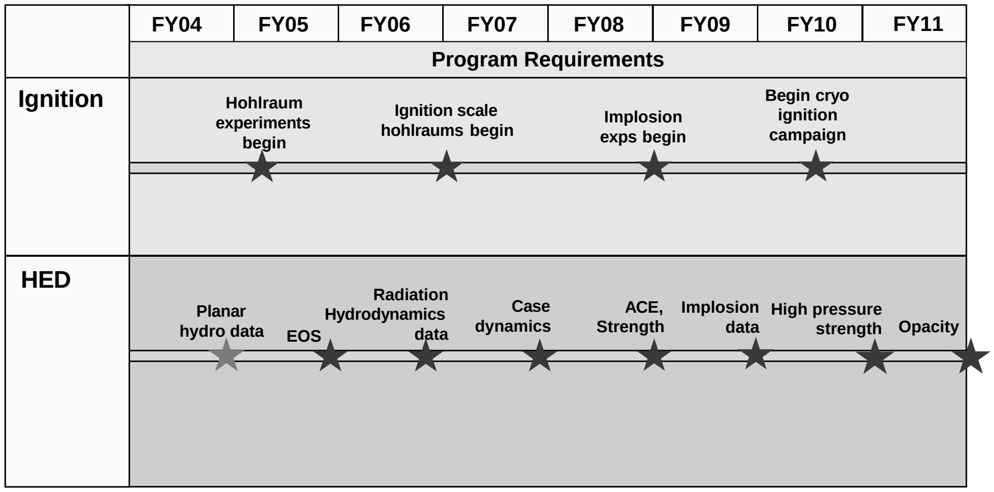



Figure 42: NIF program goals include start of cryo ignition campaign in FY 10 and yearly high energy density physics data.

For the ignition campaign, the major milestones are: (i) completion of the pre-ignition cryogenic system (FY2006); ii) start of implosion experiments in FY2008; iii) completion of the fill-tube cryogenic system (FY2009).

Figure 43 summarizes facility requirements for the first quad experiments required for planar hydrodynamics and equation-of-state.

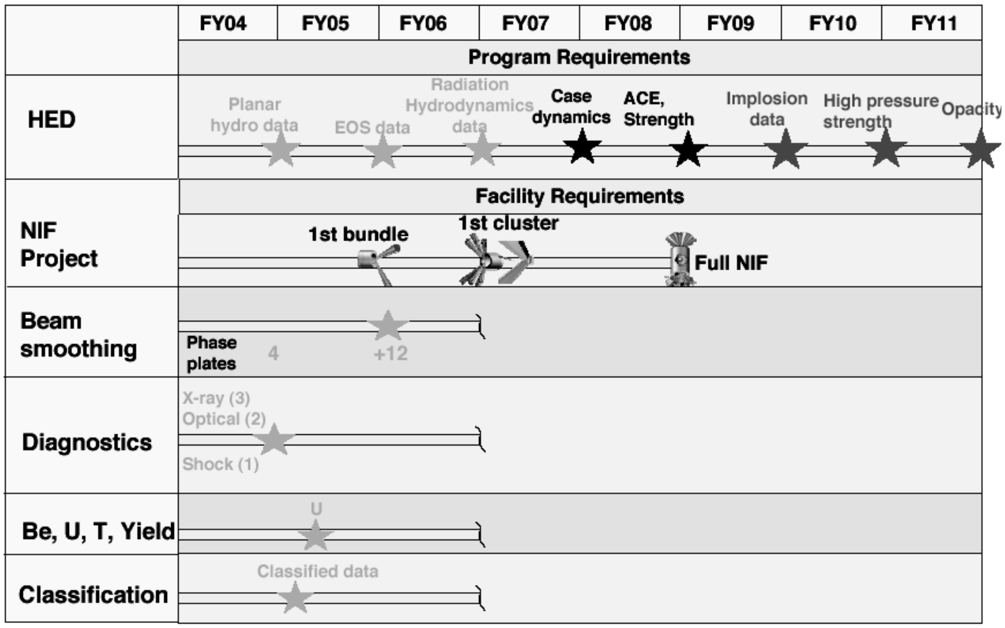



Figure 43: First quad experiments allow planar hydrodynamics and equation-of-state data; First Bundle capability enables radiation-driven experiments.

The required NIF capabilities for the first cluster experiments in radiation transport and extension of materials strength are summarized in Figure 44.

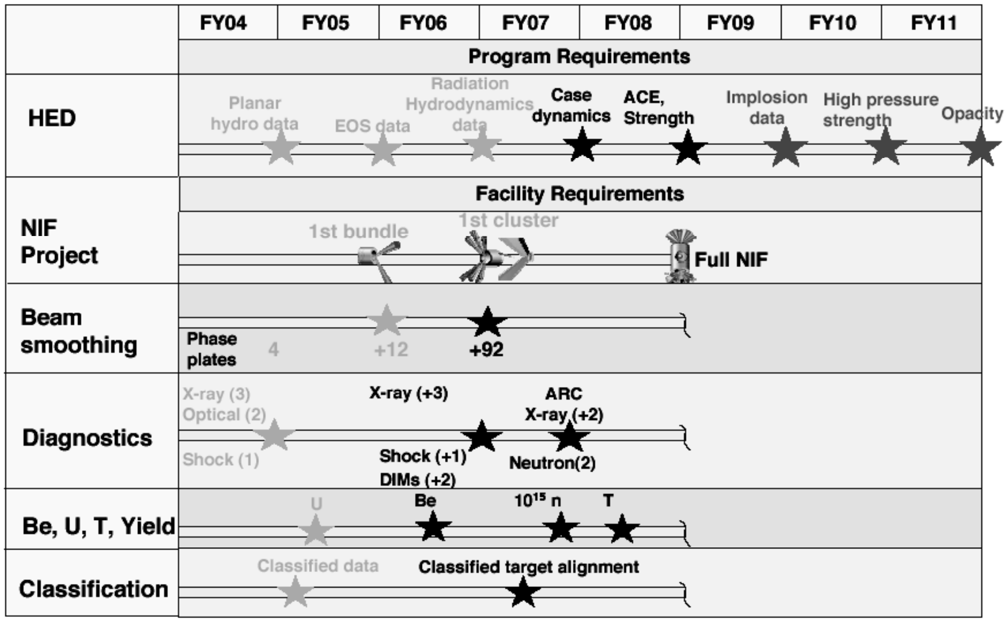



Figure 44: First cluster allows radiation driven experiments and planar material strength experiments.

Full NIF (Figure 45) will allow further weapons physics experiments involving symmetric implosions and a variety of additional Stockpile Stewardship activities.

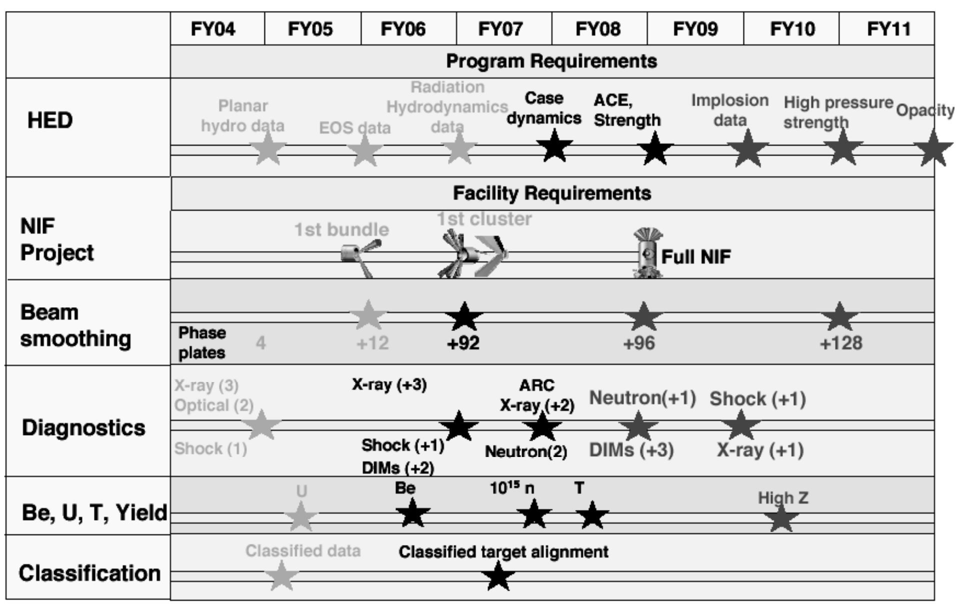



Figure 45: Full NIF allows implosion experiments and the entire suite of stockpile experiments.

Figure 46 summarizes how the NIF project and the experimental supporting technologies are being brought together in a self-consistent way to meet the needs of the integrated NIF activation and early use plan. This plan integrates the requirements from both the stockpile experiments and ignition experiments. Common use of platforms and components has been identified from the requirements of each plan, resulting in an integrated set of requirements that have a large overlap between the two plans.

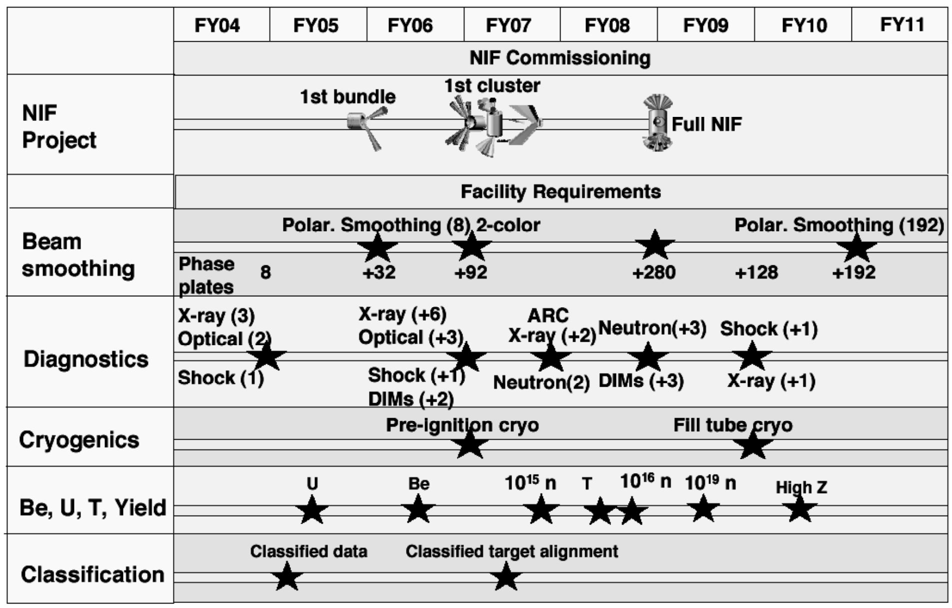



Figure 46: NIF capabilities and experimental technology support schedule.

The safety authorization basis for each phase of the experimental plan must be completed before the facility will be allowed to proceed.

# APPENDIX F: INERTIAL CONFINEMENT FUSION PROGRAM FACILITIES

## F.1. THE NATIONAL IGNITION FACILITY

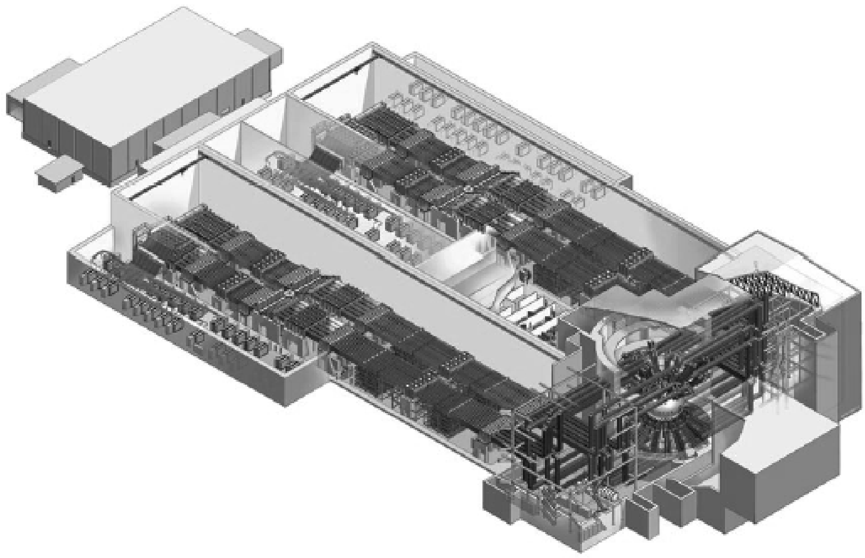


Figure 47: The National Ignition Facility.

When completed in 2008, the NIF will be a 192-beam neodymium (Nd) glass laser capable of producing 1.8 megajoules (MJ) of 351 nm energy at pulse widths from 0.1 to 25 ns. The beams are transported to the target chamber where they irradiate targets for performing experiments studying weapons physics and ignition using deuterium and tritium fuel. The entire facility has a footprint of approximately 20,300 square meters, including a reinforced concrete and steel laser building with two laser bays and a heavily shielded target area containing the final laser focusing optics, target chamber, and diagnostics. Adjacent to the target area are the diagnostics building for supporting experiments and the optics assembly building.

The laser beams are configured to illuminate a target with a specified symmetry, uniformity, and pulse shape. The laser pulse originates as a precisely formatted low energy pulse, then is amplified and distributed to the 192 beams simultaneously. Using a multipass architecture, the pulses are amplified in each of the beams at a 40 cm by 40 cm aperture in groups of eight, called "bundles". In the target area, the laser light frequency is tripled to 351 nm wavelength and focused on the target. Beam geometry is arranged for indirect drive ignition (IDI), although in the future it can be reconfigured for direct-drive ignition (DDI). These ignition concepts were discussed in Section E.3.

The target area includes a 10-m diameter, low activation aluminum vacuum chamber, which together with the building, provides confinement of radioactivity (e.g., x-rays, neutrons, tritium, and activation products). Diagnostics will be arranged around the chamber for a variety of experiments. Structural, utility, and other support systems necessary for safe operation and maintenance will also be provided in the target area. The target chamber, target diagnostics, and staging areas will be capable of conducting experiments with cryogenic targets required for ignition.

Thousands of optical components will be required for the 192-beam NIF. These components include laser glass, lenses, mirrors, polarizers, deuterated potassium dihydrogen phosphate crystals, potassium dihydrogen phosphate crystals, pulse generation optics, debris shields and windows, and the required optics coatings. Optics includes quality control equipment to receive, inspect, characterize, and refurbish the optical elements.

Construction of the conventional facilities is complete. First cluster testing is projected to occur in late FY 2006, with project completion (192 beams) in late FY 2008.

| | |
|---|---|
| Energy | 1.8 MJ |
| Peak Power | 500 TW |
| Wavelength | 0.35 μm |
| Pulse shape | Continuous or discrete |
| Pulse duration | Up to 25 ns |
| Dynamic range | 50:1 |
| Pointing accuracy | 100 μm |
| Spot size | 140 μm – 600 μm |
| Pre-pulse power | <$10^8$ W/cm$^2$ |

Figure 48: NIF Performance Parameters

## F.2. OMEGA AND OMEGA EP

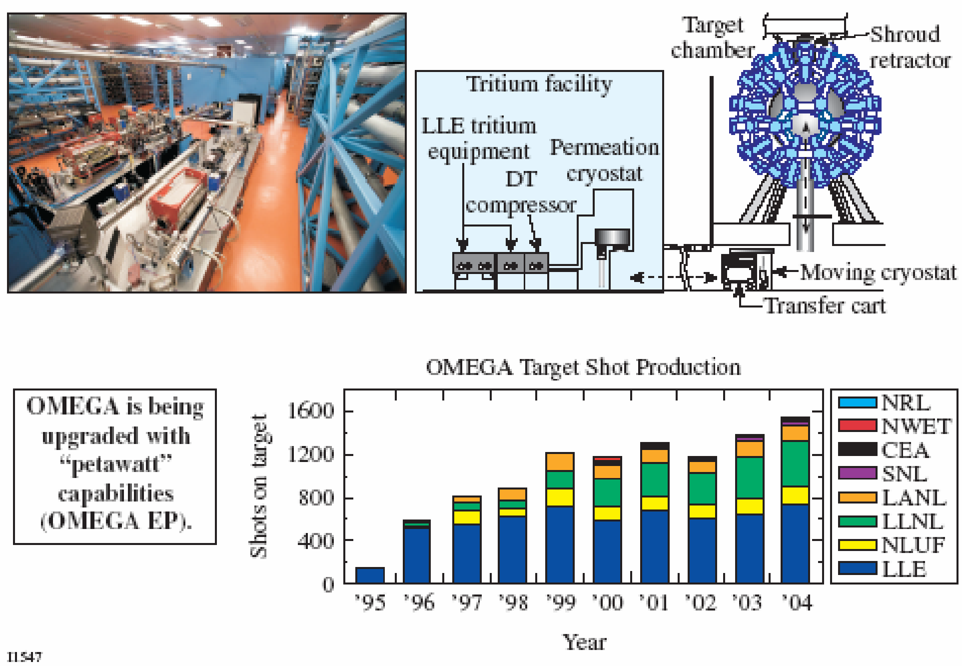



Figure 49: OMEGA (top left) is a sixty-beam UV laser facility that can irradiate cryogenic DT capsules (cryogenic system schematic at top right). OMEGA produces over 1400 target shots per year - over half of them for programs by the National Laboratories and the National Laser Users Facility.

The 60-beam OMEGA system is an extremely flexible, 30 kJ, ultraviolet (351-nm), pulse-shaped, laser system. It was designed to study the physics of direct-drive ICF under near-ignition conditions. This includes implosions of ignition-scaled cryogenic targets and studies of hydrodynamic and laser-plasma instabilities relevant to high-performance, direct-drive target implosions. In recent years, as can be seen in the plot of the number and types of OMEGA shots, the system has been successfully used by LLE and the national laboratories for a wide variety of indirect-drive and high energy density physics experiments.

As the NIF becomes operational, OMEGA will continue to be important both as an HED physics facility and as a staging facility for the NIF. This research will include development of diagnostic techniques to be applied to the NIF, physics experiments to support the national ignition plans, high energy density physics experiments, development of advanced ignition concepts, and development of university user experiments.

Currently the OMEGA laser system is the only facility capable of investigating the physics of cryogenic thermonuclear fuel implosions. The Cryogenic Target Handling System has required significant effort over the past few years and is now available for routine monthly operation. This system will be further enhanced with the introduction of cryogenic DT operations in the mid FY05 timeframe. Layering studies and target implosions using DT fuel will provide critical information concerning the limits of possible smoothing of DT ice layers and the effect of such layers on overall target performance prior to the operation of the NIF.

LLE will further expand its research capabilities by adding two, high energy petawatt(HEPW) beamlines to OMEGA: OMEGA Extended Performance (OMEGA EP). Since mid 1995 when OMEGA was constructed, progress in laser technology has included the development of high-power, high-energy laser systems using chirped-pulse amplification (CPA) and the NIF multipass architecture. Incorporating these new technologies through the addition of the OMEGA EP will modernize OMEGA and significantly expand the range of HED physics experiments carried out during the second half of this decade and beyond.

The primary system requirements for OMEGA EP are the addition of two short-pulse (1~100 ps), high power, high-energy (2.6 kJ each) beams to OMEGA. This was motivated by two primary needs:

- To provide OMEGA with a short-pulse, high-energy backlighting capability for new HED physics experiments under conditions that also allow the development of backlighting techniques for the NIF, including backlighting direct-drive cryogenic implosions; and
- To carry out integrated fast-ignition experiments on OMEGA using its unique cryogenic target implosion capability.

In addition, combinations of OMEGA and OMEGA EP will be used to create extreme states of matter relevant to high energy density physics and to study relativistic laser-matter interactions.

The design consists of two NIF-like laser beams with new target and compression chambers, relying heavily on proven CPA and NIF technology and engineering design. The beams will use CPA to provide high-energy short pulses that can be routed into either the OMEGA or the OMEGA EP target chamber. With a modest increase in project scope, two additional beams could be added and all four beams operated in long-pulse mode (1 to 10 ns) with up to 25 kJ UV energy into the OMEGA EP target chamber. This flexibility would significantly extend the HED physics capabilities of OMEGA EP, maintaining LLE's ability to perform forefront HED science.

The design parameters for OMEGA and OMEGA EP are given in Figure 50.

| | |
|---|---|
| **OMEGA** | |
| Energy on target | Up to 30 $kJ_{UV}$ |
| Lasing medium | Nd-doped phosphate glass |
| Number of beamlines | 60 |
| Irradiation nonuniformity | 1~2% rms. |
| Beam to beam energy balance | 1~2% rms. |
| Repetition rate | 1 shot per hour |
| **OMEGA EP** | |
| Number of beamlines | 2 |
| Energy per beamline | Up to 2.6 $kJ_{IR}$ (short pulse) |
| Pulse duration | 1~100 ps |
| Relative beam timing | 0~100 ns |
| Synchronization with OMEGA | 10 ps rms. |
| Repetition rate | 1 shot every 2 hours (minimum) |

Figure 50: OMEGA and OMEGA EP design/performance parameters.

## *F.3 Z ACCELERATOR*

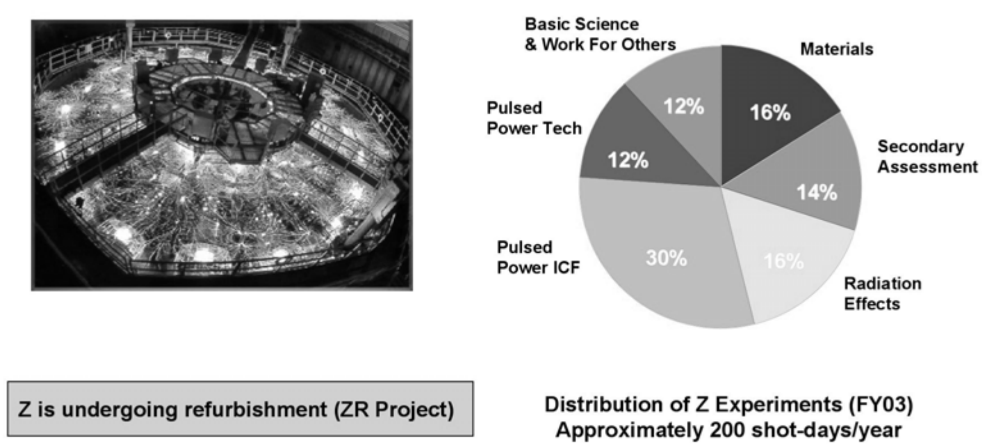



Figure 51: The Z accelerator and the distribution of experiments (FY 2003)

The Z pulsed-power accelerator provides critical experimental data to the Stockpile Stewardship Program (SSP) by converting stored electrical energy into submicrosecond, high-power electrical pulses. In particular, Z provides data for five SSP campaigns: Dynamic Materials Properties, Secondary Certification, Nuclear Survivability, Inertial Confinement Fusion (ICF) and High Yield, and Advanced Simulation and Computing (ASC). Z experiments also support the Directed Stockpile Work (DSW).

Z operates in either a z-pinch mode by vaporizing and imploding an array of 200-400 wires that are each a few microns in diameter to provide x rays, or in a short-circuit mode to provide intense magnetic fields. In the z-pinch mode, Z routinely produces more than fifty times the x-ray energy and a factor of five more x-ray power than any currently operating laser. In the short-circuit mode, isentropic compression experiments and magnetically accelerated flyer plate experiments are producing accurate high-pressure equation-of-state data.

Z’s predecessor, the Particle Beam Fusion Accelerator (PBFA) II, was constructed for the ICF Program in 1985 to produce high voltages (10-30 mega volts [MV]) to focus light ions on pea-sized capsules, producing fusion. In 1996, PBFA II was modified to a high-current, low-voltage (20 mega ampere [MA], 2.5 MV) configuration by replacing the inner 4.5 m of the accelerator. The z-pinch experiments with the modified facility were so successful that, by mid 1997, the facility was renamed Z, and light ion research was discontinued a year later. Today, Z and the OMEGA laser at the University of Rochester are the major operational, HEDP facilities at the National Nuclear Security Administration (NNSA) national laboratories.

During the last four years, incremental improvements in daily processes have been made, innovative methods to reduce experimental preparation time have been developed, and an extensive suite of time- and space-resolved diagnostics has been added. In FY 2000, a new control monitor system was implemented that adopts modern industrial control technology.

The ZR project will enable the Z facility to continue providing vital SSP, ICF, and HEDP data well into the next decade. Refurbishing Z with modern, conventional technology and systems optimized for z-pinches and designed for durability will significantly increase shot capability, enhance precision and pulse shaping variability, and increase output current. Benefits will accrue not only to existing experimental programs, but will advance new programs that can't be realized without refurbishment. In addition, refurbishment of the Z Accelerator will sustain and extend pulsed power expertise at Sandia, which could be lost unless meaningful and challenging work is maintained.

The Z Refurbishment Project has four major objectives:

- Provide for increased utilization of Z by providing the capability to perform more shots,
- Improve overall precision and pulse shape variability for better reproducibility and data quality,
- Increase delivered current allowing for additional performance capability, and
- Accomplish these improvements with minimal disruption to Z's ongoing experimental programs.

The characteristics of Z and ZR are summarized in Figure 52.

| Capability | Z Today | After Refurbishment |
|---|---|---|
| Power Radiated (Nested Arrays) | 230 TW | 350 TW |
| Energy Radiated (Single Array) | 1.6 MJ | 2.7 MJ |
| $T_r$ for Radiation Physics VH/DH | 140 / 215 eV | 165 / 260 eV |
| $T_r$ for ICF VH/DH | 70 / 215 eV | 85 / 260 eV |
| $P_{pk}$ for ICE (Cu) | 3.25 Mbar | 10 Mbar |
| Flyer Plate Velocity | 27 km/s | > 40 km/s |
| In band energy 1 keV / 5 keV / 8 keV | 450 / 100 / 18 kJ | 900 / 300 / 72 kJ |

VH = Vacuum Hohlraum DH = Dynamic Hohlraum ICE = Isentropic Compression Experiments

Figure 52: Experimental Capability of Z and the Proposed Refurbished Z Machine

## F.4 NIKE

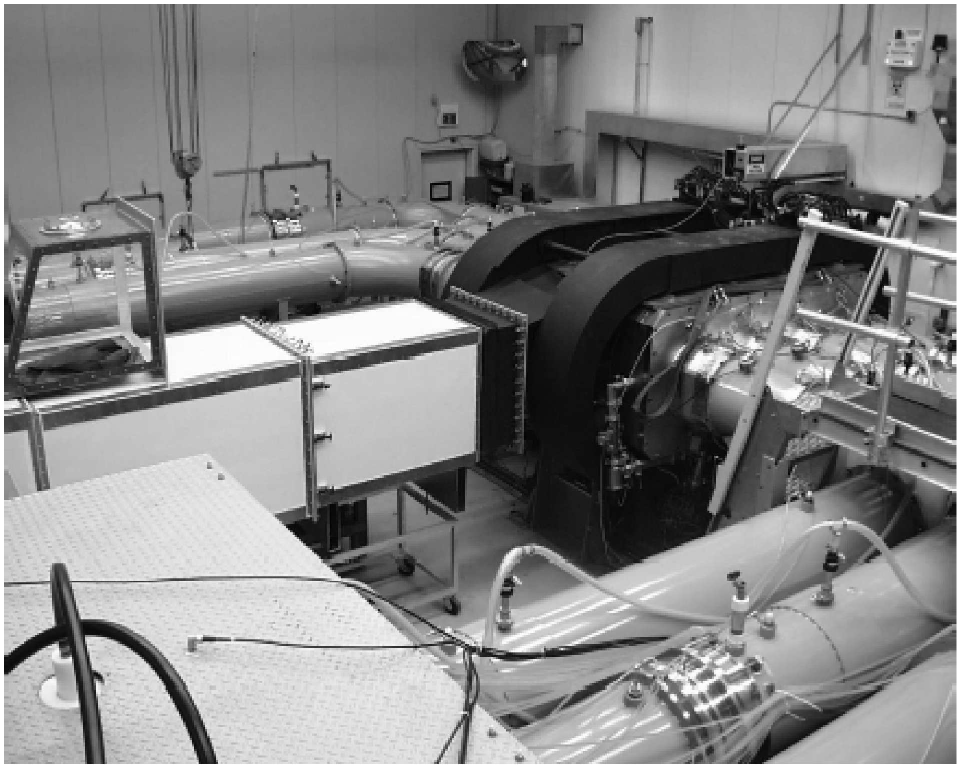


Figure 53: The Nike KrF laser facility.

The 56-beam krypton fluoride (KrF) Nike gas laser produces 4,000-5,000 J of UV light in a 4-ns pulse. Nike's unique feature is its excellent beam uniformity, about a factor of ten better than the best existing short-wavelength glass lasers. By using a KrF laser with induced spatial incoherence (ISI) optical smoothing, the modulations in the laser focal profile are only one percent in one beam and <0.3 percent with a 44-beam overlap. Nike is used in laser-target experiments, to determine if this laser uniformity is necessary and sufficient to accelerate a direct-drive target under fusion-like conditions, without excessive hydrodynamic distortion or fuel preheat.

Early research with Nike emphasizes the science of laser fusion. The laser also has several other possible applications:

- Uniform and cold compression of materials to 3-5 Mbar;
- Efficient generation of multi-keV x-rays with low debris, to simulate nuclear weapons effects; and
- Interaction of 10-20 Mbar uniform shocks, with non-uniform material structures, to aid evaluation of the aging nuclear weapons stockpile.

The propagation bay for the laser system is a 155-ft long insulated room. The temperature throughout can be held uniform, to within a half degree Fahrenheit, so that a diffraction-limited beam can propagate back and forth, without distortion. Charcoal filters eliminate ultraviolet (UV) absorbing gases. At each mirror array, all 56 beams can be simultaneously aligned, in a few seconds, by an automatic alignment system. The 60 cm by 60 cm KrF amplifier cell is pumped from two sides by identical electron beams generated from Marx banks. The large magnetic field coils of 2-4 kG are used to guide the electron beams through the gas cell. The Nike laser system uses both discharge preamplifiers and E-beam pumped amplifiers. Because the E-beam amplifiers have a long-pulse duration, the laser beams are "multiplexed" into 56 separate beams that pass through the amplifier successively and are then recombined onto the target. Forty-four of the beams are used for target acceleration and twelve are used to produce a backlighter for target diagnostics.

Nike uses planar foil targets. This geometry is better suited for evaluating the imprint by laser non-uniformities and for diagnosing growth of the more damaging Rayleigh-Taylor instability modes. The experiments use target thicknesses, target materials, laser pulse durations, and laser pulse shaping that match the parameters of a high-gain direct-drive fusion target as closely as possible. High-mode capsule perturbations can be evaluated using flat foils. Lower-mode, spherical perturbations are better studied, with glass-laser implosion facilities.

| | |
|---|---|
| Laser Energy | 5 kJ |
| Optical bandwidth | 3 THz |
| Beam quality | 0.2% |
| Pulse length | 4 ns |

Figure 54: Nike Characteristics

## F.5 SMALLER SUPPORTING FACILITIES

### F.5.1. Trident Laser

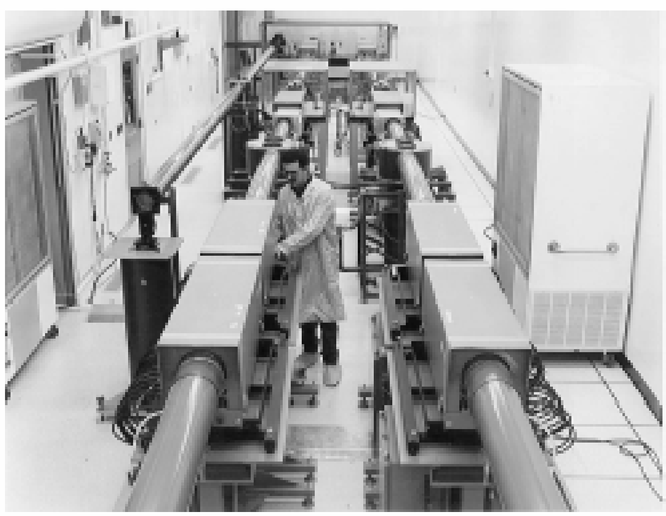


Figure 55: Trident Facility

The Los Alamos Trident Laser Facility provides the capability to conduct basic HED experiments, advanced diagnostic development, and prototyping and staging of experiments that will transition to larger facilities. Trident (operated by the Los Alamos ICF / Thermonuclear Experiment (TNX) Program) principally supports the NNSA DP ICF and HEDP Programs (C-1, C-4, C-10), but also has a basic research component that involves other laboratories and the academic community.

Trident is a neodymium-glass laser, capable of delivering energy of up to 400 joules, at a wavelength of 1.054 nm, in a 1-ns pulse in each of two 20-cm beams, and up to 40 joules in the 10-cm "C-beam". The two 20-cm beams (A & B) are frequency converted to the second harmonic (527 nm) before being focused onto the target. The C-beam is synchronized to the A and B beams and can either be operated in the fundamental, or in the 2nd or 3rd harmonic.

The Trident system has 2 large target chambers providing for considerable flexibility and efficiency in conducting experiments. One of these chambers is compatible with a ten-inch manipulator (TIM), which is the ICF standard for positioning diagnostics on NIF and OMEGA. Check out and testing of TIM-based diagnostics is anticipated to be a major activity in the next few years. This capability supports diagnostic development for OMEGA, Z and especially the National Ignition Facility (NIF).

The Trident laser system has a number of unique capabilities that enhance its roles in diagnostic development, experiment staging and basic physics. The "C" beamline ("backlighter beam") can be configured to provide near diffraction-limited performance, with modest energy. This has allowed a number of experiments to be performed that require the interaction of a single laser speckle with a pre-formed plasma. This in turn has produced fundamental information on laser plasma interactions that is being extrapolated to the conditions that will be encountered at NIF.

Trident also has extensive ultrashort pulse, high intensity capability. This enables it to be used in forefront work in ultrahigh intensity laser matter interactions including the development of high photon energy radiography.

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# APPENDIX G: ACRONYMS

| | |
|---|---|
| ARC | Advanced Radiographic Capability |
| ASAP | Academic Strategic Alliances Program |
| ASC | Advanced Simulation Computing |
| ASCI | Accelerated Strategic Computing Initiative |
| CEA | Commissariat à L'Énergie Atomique |
| CPA | Chirped-pulse Amplification |
| D1 | Design 1 |
| D2 | Design 2 |
| D3 | Design 3 |
| DARHT | Dual-Axis Radiographic Hydrodynamic Test |
| DDI | Direct-drive Ignition |
| DOE | Department of Energy |
| DP | Office of Defense Program |
| DSB | Defense Science Board |
| DSW | Directed Stockpile Work |
| DT | Deuterium-tritium |
| EOS | Equation of State |
| EP | Extended Performance |
| EST | Experiment Support Technology |
| FABS | Full Aperture Backscatter System |
| FXI | Flexible X-ray Imager |
| GA | General Atomics Corporation |
| HED | High energy density |
| HEDP | High-energy-density physics |
| HEPW | High Energy Petawatt |
| ICF | Inertial Confinement Fusion |
| ID | Indirect drive |
| IDI | Indirect-drive Ignition |
| IFE | Inertial Fusion Energy |
| ISI | Induced Spatial Incoherence |
| KrF | krypton fluoride |
| LANL | Los Alamos National Laboratory |
| LLE | Laboratory for Laser Energetics |
| LLNL | Lawrence Livermore National Laboratory |
| LMJ | Laser Megajoule |

| | |
|---|---|
| LPI | Laser-plasma interactions |
| MJ | Megajoules |
| NBI | Near Backscatter Imager |
| NCTS | NIF Cryogenic Target System |
| Nd | Neodymium |
| NEL | NIF Early Light |
| NIF | National Ignition Facility |
| NIF EST | NIF Experimental Support Technologies |
| NLUF | National Laser User Facility |
| NNSA | National Nuclear Security Administration |
| NRL | Naval Research Laboratory |
| PBFA | Particle Beam Fusion Accelerator |
| PDD | Polar Direct Drive |
| QMU | Quantification of Margins and Uncertainties |
| RTBF | Readiness in Technical Base and Facilities |
| SNL | Sandia National Laboratories |
| SSAA | Stewardship Science Academic Alliances |
| SSP | Stockpile Stewardship Program |
| SXD | Streaked X-ray Detector |
| SXI | Static X-ray Imager |
| TIM | Ten-inch Manipulator |
| TNX | Thermonuclear Experiment |
| UR/LLE | University of Rochester, Laboratory for Laser Energetics |
| UV | Ultraviolet |